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Innovations in Ventilative Cooling

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Innovations in Ventilative Cooling

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Preface

Energy use for space cooling and ventilation is consistently increasing and this is expected to continue at an even higher speed in future years. This challenge requires alternative solutions to reduce energy needs and improve thermal and IAQ comfort conditions in building spaces. Ventilative cooling systems and strategies are faced in this book, which is being considered to be one of the most promising possibilities to face this challenge. This book benefits from research and professional practice in the ventilative cooling field, supported by the selected panel of authors and by past and current researches and applications on the ventilative cooling topic. As regards the structure of this book, the first part (boundaries) renders the book accessible to less experienced professionals and reports main innovation issues concerning ventilative cooling implications (working principles, performance indicators, recent standards, control and actuator techniques, comfort modelling, air pollutants and others), while the following and more focused parts are principally conceived for an experienced target readership, describing ventilative cooling techniques, even combined with PCM (Phase change materials), other natural cooling solutions, and vegetation, while the applications part reports recent outcomes and lesson learnt on ventilative cooling applications in different building typologies. The contents are based on experiences, researches and case studies in the field of ventilative cooling. The authors represent a range of nationalities thus providing the opportunity to examine different local climate issues and technological backgrounds. It should be noted that particular attention has been given to low-cost solutions.

A special acknowledgment is due to all researchers, professionals and institutions have been working together in Annex 62 on Ventilative Cooling, International Energy Agency, Energy in Buildings and Communities Programme (2013–2018). This book also includes elaborations of results from Annex 62 on Ventilative Cooling, and therefore provides a unique opportunity for readers to access this information.

Annex participants are from universities, industries and consulting companies from 15 nations.

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Contents

Chapter 1
Innovations in Ventilative Cooling: An Introduction

Giacomo Chiesa, Maria Kolokotroni, and Per Heiselberg

Abstract This chapter introduces the book's contents and its structure. It also includes a short description of why Ventilative Cooling (VC) is increasing in importance in a scenario where building cooling needs are growing. The building sector is responsible for about 40% of primary energy consumption; space heating, cooling and ventilation have proved to be the main consumers. Even though great efforts have been made to reduce energy needs for space heating, much less has been done for space cooling and ventilation. However, this situation is bound to change given that energy consumption for cooling is expected to supersede that for heating between 2050 and 2100. The main features of this growth are analysed in consideration of the international style of buildings, the growth in comfort expectations and changes in comfort culture, the growth in internal heat gains, increasing air temperature and urban heat island, as well as the side effects of the advancement in building envelope optimisation to reduce winter consumption (solar gains, airtightness). In order to face these new developments, which are linked with local increases in air temperature due to the thermal by-product of conditioners and related Green House Gas emissions, natural and hybrid solutions are needed. This book focuses on Ventilative Cooling techniques which aim to be a complete and reliable reference for designers and engineers who are working in the field of environmental design and renewable energy in the building sector. In this book Ventilative Cooling boundaries including all relevant information, background issues, techniques and applications are discussed based on the work of an internationally recognised group of experts. This chapter contains a short description of the contents of each part of the book.

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1.1 Background: Cooling Needs and Overheating Phenomena

Overheating of building spaces is a worldwide rising issue impacting at early-design, advanced-design, and operational stages [1]. This challenge is evident in all climate conditions, from heating-dominated regions to cooling-dominated ones, forcing cooling energy demands and increasing the world population living in uncomfortable indoor conditions due to lack of resources—a number that has grown to more than one billion of people [2]. The growing cooling demand to avoid overheating refers to several causes [3, 4]. In particular, at building level, the international style of buildings has produced a lack in bioregionalism detaching building envelopes from local climate and driving the provision of comfort in internal spaces by mechanical systems. Furthermore, current standards in several regions, such as Europe, are requiring high performances by new and retrofitted buildings focusing on the need to reduce heating demand by implementing high insulation levels and reduced infiltration. This approach, driven by heating dominated climates, needs to be faced carefully in warmer climates due to negative effects on overheating conditions, a challenge now evident even in colder climates during building operations [5, 6]. This effect can be shown by analysing the statistically ranked effects on energy outputs in building dynamic simulations. As an example, results for the Italian climate zones indicate a cooling dominant demand even in colder areas due to the increase in the heating related measures [7]. Additionally, rising in ambient temperatures result to increase overheating risks. This challenge is connected to climate changes and to urban heat island phenomena with a relevant impact on building operation in summer seasons—see Sect. 1.1. This effect has a high impact on building cooling needs, due to the high difference between the local Typical Meteorological Years (TMYs), which are generally used in design phases, and real climate under which buildings operate [8]. In addition, changes in the comfort culture and an improvement of life standards have driven the installation of new cooling units requiring more energy. Finally, a general increase in internal gains—e.g. by electronic devices—is observed during operational phases resulting to an increase in overheating and cooling energy needs. All of these aspects impact on building cooling demand and increase the energy "performance gap" due to an evident deviation between predicted energy demand at design stage and energy use during the operational phases. Several post-occupancy works underline a significant higher energy use in respect to the predicted one and a parallel overheating issue [1]. Studies based on climate models considering climate change scenarios, suggest that in 2100 cooling energy needs will overpass heating ones, even in several locations that at present have a heating-dominated climate [9].

Energy demand for space cooling has quickly growth during recent decades, reaching in 2010 a global consumption for cooling of 1.25 PWh [10, 11], a number which is still growing. This is due to the increase in the number of overheating hours, overheating intensity, and the number of installed cooling units. This trend is not only influencing areas where cooling systems have a high market penetration, such as Japan and U.S., but is also evident in fast-developing countries, such as

China, India, Brazil, and also at European level [2, 12]. In developing countries, air-conditioning industry has shown an evident growth in their market, which, in some cases, has registered a +70% increase in the period 2010–15, from 9 Billion to 16 Billion USD [13]. Additionally, in China the number of installed air-conditioners is growing almost exponentially, and was expected to reach 120 million of installed units in the warm areas in 2017 [14]. It is hence evident, that such an increase at global level requires alternative solutions to mitigate the growth in electricity consumption, to reduce electricity peak costs, prevent blackout risks, and avoid additional $CO_{2\text{-eq}}$ emissions.

Ventilative cooling is a potential solution to these challenges because of its ability to dissipating heat gains using the external air as a thermal sink, especially in climates where ambient temperature and humidity are lower than internal thermal comfort requirements. Referring to IEA EBC Annex 62 [15], Ventilative Cooling (VC) defines "natural or mechanical ventilation strategies to cool indoor spaces" by mixing outside low-temperature air with inside one to decrease energy needs of cooling systems and maintain thermal comfort conditions. Probably, one of the most known ventilative cooling mode is night ventilation (structural ventilation) based on increase ventilation airflows at night time [16], while other modes are for example environmental ventilation (cooling by air exchanges) and personal ventilation (direct airflows flushing on human bodies). VC is a very relevant technology applicable in an extensive range of building typologies to dissipate heat gains by activating the external air natural sink [17]. Main current use of ventilation principally refers to the replacement in a time unit of a given quantity of air in indoor spaces with the same amount of fresh air to guarantee indoor air quality (IAQ), nevertheless its potential for energy space cooling reduction is evident [18], acting on heat gains and air velocity. It is essential to support this solution by acting on standards and regulations, in order to allow to correctly valorise its potential, and supporting the diffusion of appropriate technical solutions [19].

1.1.1 Impact of Climate Change

As mentioned before, local and global climate change result on higher ambient temperatures and consequent overheating issues in building spaces. Climatic conditions have a direct effect on the building cooling loads, and this depends on air temperature, humidity, solar radiation intensity, and wind flows (speed and direction). Among a large number of indicators coupling building cooling energy needs and climate variables, the Degree-Hours index, a cumulative indicator, was adopted by several scientists [18, 20–22]. In addition, ISO 7730 and EN 15251 include the Degree-hours criterion by analysing the occupied hours that indoor operative temperature is above the upper operative temperature comfort limit—for a review of ventilative cooling-connected comfort indices see also [1, 23]. The Cooling Degree Hours (CDH) indicator is defined as follows:

$$CDH = \sum \left\{ \begin{matrix} \vartheta_{amb} - \vartheta_b \Rightarrow \vartheta_{amb} > \vartheta_b \\ 0 \Rightarrow \vartheta_{amb} \leq \vartheta_b \end{matrix} \right\} \quad (1.1)$$

where ϑ_{amb} is the hourly ambient temperature and ϑ_b the base temperature adopted to CDH calculation, defining a balance between ambient temperature and discomfort. This last indicator is generally ranging between 18.3 °C (ASHRAE) and 26 °C [24].

The CDH or the CDD, (which combines the hours to days), were correlated with high R^2 with the local cooling energy demand and the market penetration of air conditioners—see for example [20, 25]. CDH and CDD may also be used to define the impact of climate change on cooling energy demand. At macro-regional level, several researches have shown a global increase in CDD or CDH [11, 26] considering several case studies or focusing on specific regions, such as China [27], Switzerland [28], Africa [29], and the U.S. [22, 30].

A study of the CDD and HDD trends defined at average yearly base for EU-28 countries was carried out by elaborating Eurostat data [31] and is shown in Figs. 1.1 (CDD) and 1.2 (HDD). Figure 1.1 clearly shows how warmer regions have becoming hotter during the past 43 years, while a general increase in CDD is underlined at whole EU-28 level with an R^2 of 0.7039. In contrast, Fig. 1.2 shows a slow decreasing trend during the same period for almost all countries and at EU-28 average, but the R^2 is lower at 0.4.

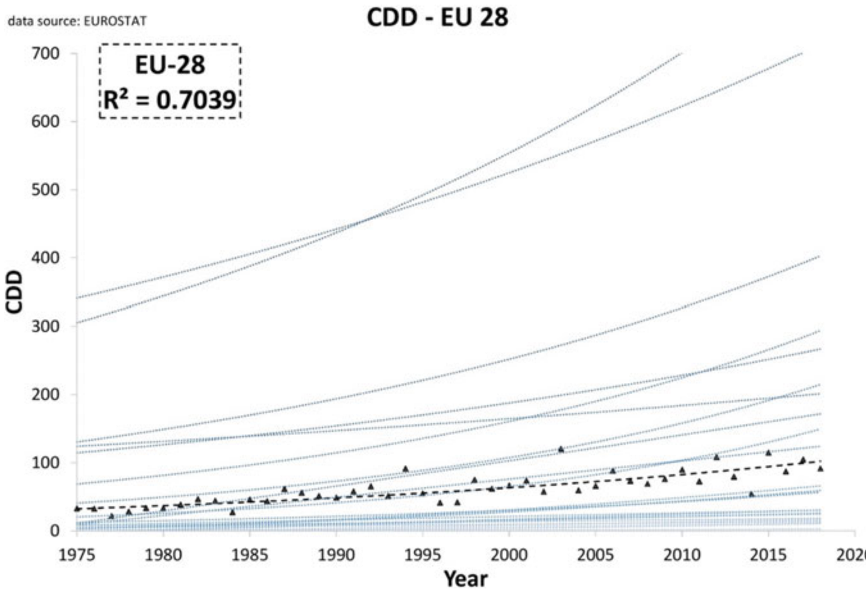

Fig. 1.1 CDD trends for EU-28 countries—average yearly data from 1975 to 2018. Blue dotted lines are regression *polynomial curves calculated for each EU-28 country, while the black dotted line is the regression trend for the average EU-28 data based on yearly value (triangular points). The R^2 value is sufficiently high to define that a general growing trend is evident for CDD in average EU-28 data (elaboration on Eurostat data)*

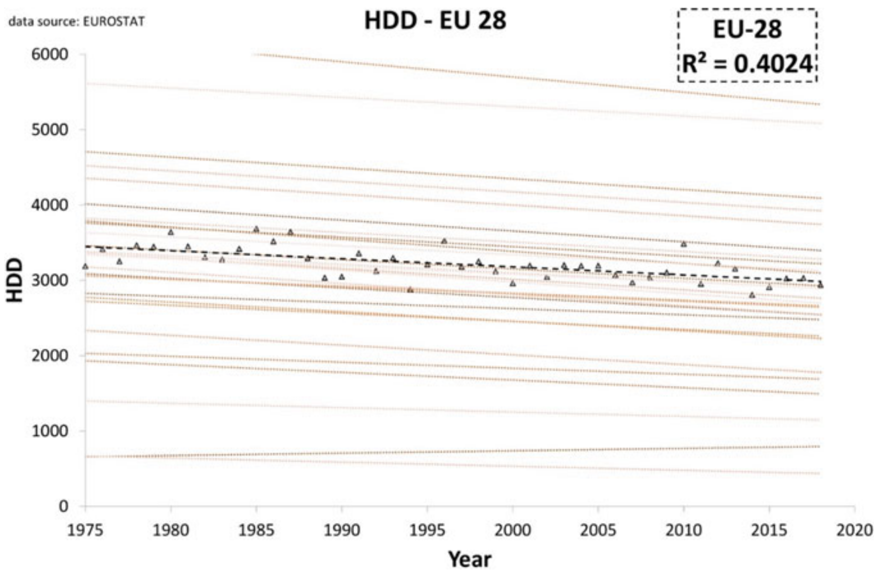

Fig. 1.2 HDD trends for EU-28—average yearly data from 1975 to 2018. Orange dotted lines are regression curves calculated for each EU-28 country, while the black dotted line is the regression trend for the average EU-28 data based on yearly value (triangular points) (elaboration on Eurostat data)

Focusing on three sample countries (Denmark, Belgium, Italy), the 10-year average CDD index was calculated using the same database (Eurostat) to analyse general trends. Furthermore, the percentage variations in respect to the 1975-84 period were generated. Figure 1.3 shows respectively the average values (a) and the percentage variation (b). Figure 1.3 shows more clearly the effect shown in Fig. 1.1, illustrating that in warmer areas the increase in CDD over time is evident, while in colder areas impacts less at average level. A similar result was also presented in [26]

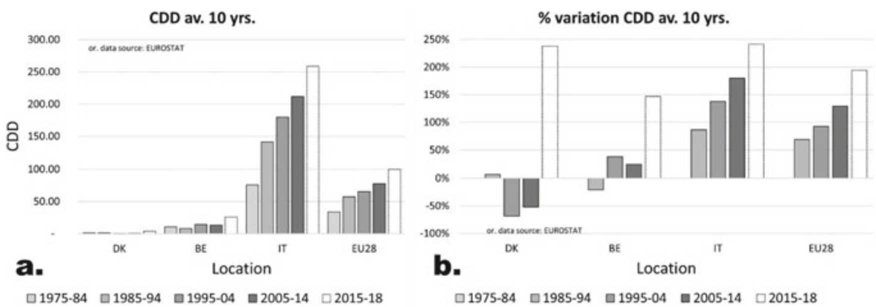

Fig. 1.3 10-year average CDD trends considering **a** CDD values and **b** percentage of the variation in respect to the 1975–1984 reference decade—elaboration on Eurostat data

on the base of 144 case studies. Nevertheless, it was demonstrated, by analysing mortality rates, that people living in heating-dominated locations are less resilient to temperature increasing, i.e. during heat waves, in respect to people living in cooling-dominated areas [32]. In the three example countries and in EU-28, average values show a rapid increase in CDD for the recent period, suggesting that ambient temperature increases will increase cooling loads demanding additional cooling energy in buildings.

The values presented in Figs. 1.2 and 1.3 were mapped in Fig. 1.4. In Fig. 1.4 NUTS (Nomenclature of Territorial Units for Statistics [33]) levels were used which is the European nomenclature of territorial units for statistics. NUTS level 2 (Regional level) was used, for Regions where this is reported, and NUTS level 0 (National level) was adopted for the others. For example, in France, only the Paris NUTS level 2 is accessible through EUROSTAT, while the other parts of the country is represented by the average country level 0 that includes both southern and northern regions. The maps in Fig. 1.4 clearly illustrate the progressive increase in cooling degree-days supporting the consequent linear behaviour of cooling energy demands. This growing trend is principally affecting, as mentioned before, warmer regions, but there is evidently a progressive increase of the warmer zone from South to North areas.

A recent study, based on a simple EnergyPlus residential unit simulated in 9 Mediterranean climates (Cs in Köppen-Geiger classification), shows a preliminary evidence on the fact that regression-based correlations between cooling demand and $CDD_{18.3}$ follow a similar trend for both current and future climates, even if datapoints are translated along the trend to higher values—see for example Fig. 1.5a concerning a naturally ventilated sample building [34]. The graph (a) includes two analyses, the first for a not insulated building (existing flat built in the 50–70s) (round points with larger dashed lines), and the second for an insulated building in line with recent building construction standards (triangular points with dotted regression lines). The same analysis correlates local cooling degree-days with correlated energy needs for cooling showing for both current TMY and future scenario a comparable regression trend with high R^2—see respectively blue and grey lines. For both scenarios, it is evident that a shift, following the same trend, on CDD and energy needs arrives between current and future predicted climate defining an expected increase in the cooling energy needs. It is hence important to verify if low energy cooling solutions, such as ventilative cooling, may cover this growth.

Hence, the priority level for ventilative cooling heat dissipation in Italy was recently analysed suggesting a slightly rise when IPCC A1B mid-scenario is assumed in comparison to current TMYs [35]. Priority levels were defined by combining local cooling demand, based in this specific study on the CDH index, and the potential heat dissipation due to ventilative cooling. Results of this analysis show that the number of locations with a very-low applicability for ventilative cooling is expected to growth in the future, due to a rise in external discomfort hours in several warmer locations when ambient air is too high to perform ventilative cooling—see Fig. 1.5b. Nevertheless, a rise was also expected for the very-high applicability class due to a

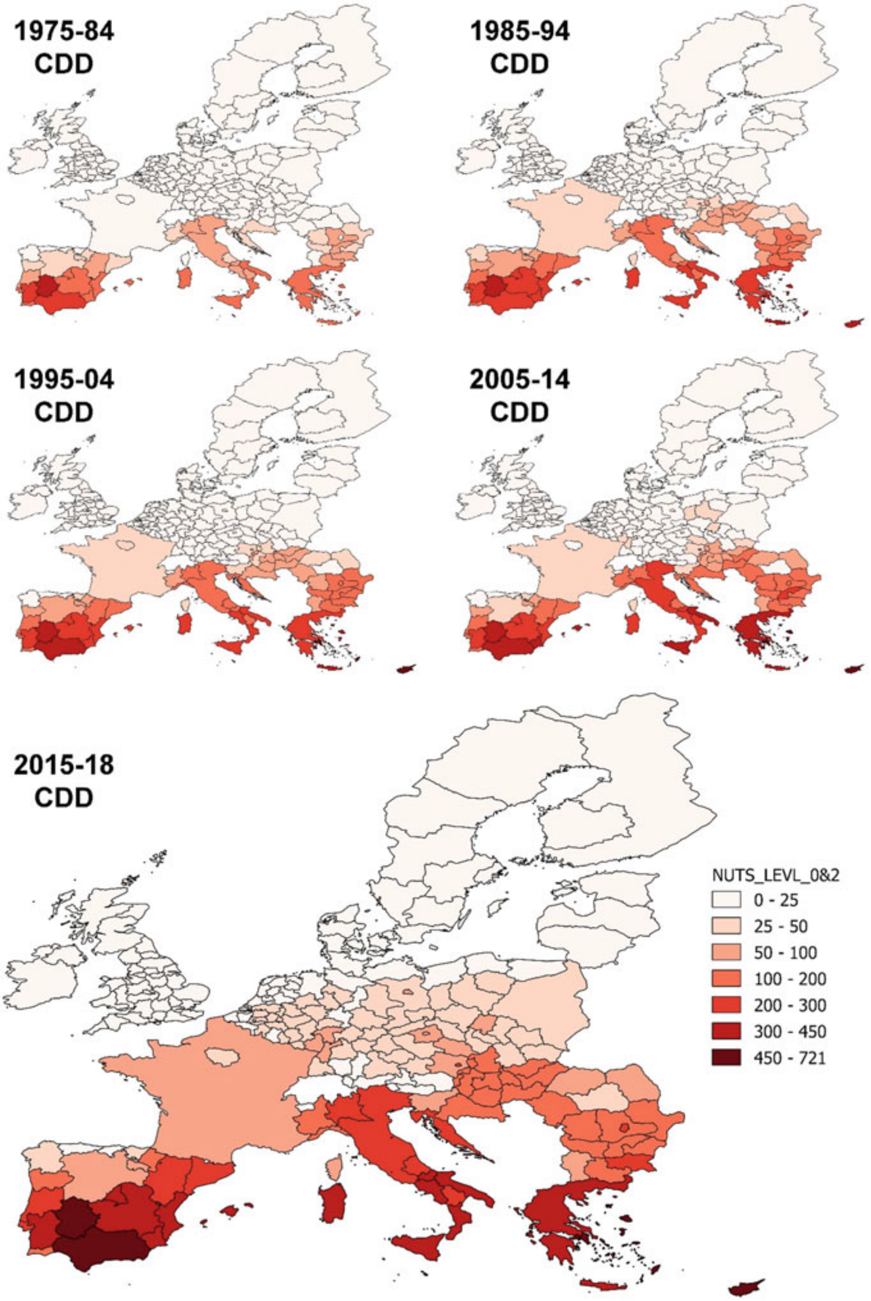

Fig. 1.4 10-year average CDD trends mapped for NUTS level 2 respectively for 1975–84, 1985–94, 1995–2004, 2005–14, and 2015–18 periods. *Note* When data of level 2 are not available NUTS level 0 is adopted—elaboration on Eurostat data

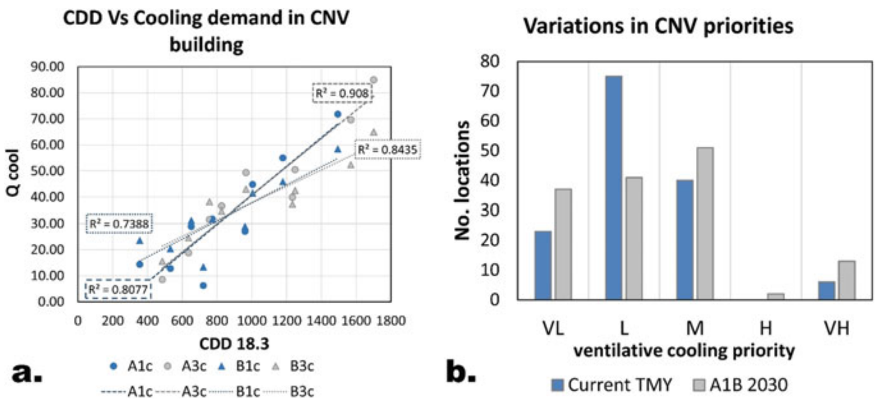

Fig. 1.5 **a** Correlation between $CDH_{18.3}$ and cooling energy needs assuming a reference residential building naturally ventilated in 9 Climate-Mediterranean locations. Case A and B are respectively for uninsulated and insulated buildings, while 1 and 3 are respectively current TMY and future A1B 2050 predicted one. Elaboration from [34]; **b** distribution of ventilative-cooling-priority classes considering current and future-scenario (A1B 2030) TMY for the Italian locations with more than 50 k inhabitants. Elaboration from [35]

higher demand for cooling in temperate locations, where the future predicted environmental air is expected to remain sufficiently low to cool spaces. Furthermore, this preliminary study shows a visible migration from low to medium priority classes—see Fig. 1.5b—thanks to an increase in the number of overheating hours showing a ventilative cooling potential.

Several studies on the topic are currently under development, while a IEA EBC Annex is now working to study "resilient cooling" solutions (Annex 80).

1.2 Innovations in Ventilative Cooling at Building and Urban Scale: Contents and Structure

This book focuses on Ventilative Cooling describing current state of the art of VC strategies and supporting VC diffusion as a valid alternative solution for space cooling and ventilation.

The book is subdivided into 3 parts defined as follows:

- Part I—Boundaries

This part introduces VC boundaries by including: i. general and specific information about VC (main principles, rules of thumb, key performance indicators (KPI), …); ii. background issues, such as comfort models for VC, standards and regulations; iii. new contents related for example to the effect of urban air pollution on VC.

- Part II—Techniques

In Part II the main aspects related to VC techniques and implications are treated in order to define a technical background for the reader and to introduce the latest research issues in the field. Specific aspects of VC are analysed including interaction with passive cooling techniques –e.g. for heat gain prevention, such as shading systems, for heat gain mitigation, such as thermal masses and phase-change materials (PCM)—, and with natural cooling systems—e.g. direct evaporative cooling (DEC), and earth-to-air heat exchangers (EAHX). Furthermore, the positive effect of vertical vegetation, the mixed usage of natural and mechanical VC and control systems are analysed.

- Part III—Applications

This third part describes how VC can be included technically in building design and how the techniques could work from an operational point of view for different building typologies. This part gives practical examples of VC usage, makes suggestions and explains case studies to professionals who are interested in including VC techniques in their projects. It focusses on the importance of controls, applicability to residential buildings (in which night cooling might be difficult to implement), tertiary buildings, and renovation of historic buildings (which have specific requirements but also opportunities because of their construction methods). Furthermore, each chapter covers a particular topic focusing in particular on residential buildings, offices and schools, and on the use of VC in historical building renovation. Additionally, a parametric analysis on ventilative cooling strategies together with climate and microclimate variations is included in the tertiary building chapter to support design actions.

Moreover, each chapter defines a specific VC topic focusing on:

- Ventilative cooling principles, potential and barriers|*Per Heiselberg, Aalborg University, Denmark*;
- Ventilative cooling and comfort models, focusing in particular on the adaptive comfort approach|*Fergus Nicol, London Metropolitan University, UK*;
- Ventilative cooling in standards and regulations, including recent proposals and released standards, and further recommendation for supporting VC applications|*Michal Pomianowski, Aalborg University, Denmark & Christoffer Plesner, Velux, Denmark*;
- Ventilative cooling and air pollution, focusing, in particular, on the minimisation of indoor PM2.5 and considering VC impact on HVAC electricity consumptions|*Guilherme Carrilho da Graça & Nuno R. Martins, Universidade de Lisboa, Portugal*;
- Ventilative cooling and control systems, analysing main control strategies to optimise VC system usage in buildings|*Hilde Breesch & Bart Merema, Ku-Leuven, Belgium*;

- Ventilative cooling in combination with passive cooling, focusing on thermal masses and PCM usage in combination with VC techniques|*Maria Kolokotroni & Thiago Santos, Brunel University, UK*;
- Ventilative cooling in combination with other natural cooling solutions, focusing on direct evaporative cooling technologies, analysing main DEC principles and defining devoted KPI|*Giacomo Chiesa, Politecnico di Torino, Italy & David Pearlmutter, Ben Gurion University, Israel*;
- Ventilative cooling in combination with other natural cooling solutions, focusing on Earth-to-Air heat exchangers, analysing main EAHX principles and technological requirements for building integration and connected KPIs|*Giacomo Chiesa, Politecnico di Torino, Italy*;
- Ventilative cooling and urban vegetation, studying the relation between green envelope technologies, heat gain prevention and positive effect on ventilation systems|*Katia Perini, University of Genova, Italy & Gabriel Perez, University of Lleida, Spain*;
- Ventilative cooling in residential buildings, describing several case studies in which VC is adopted to reach thermal comfort in buildings|*Paul O'Sullivan, Cork Institute of Technology, Ireland*;
- Ventilative cooling in tertiary buildings: description of the VC design experience for a school demo-case and a parametric analysis under Swiss climate conditions considering office, residential and school units|*Flourentzos Flourentzou, Estia SA, EPFL Innovation Parc, Lausanne*;
- Ventilative cooling in historical building renovation, analysing, using the case study of the Houses of Parliament UK, the practical application of VC over a period of 100 years, studying comfort perception|*Henrik Schoenefeldt, University of Kent, UK.*

This book allows to introduce VC issues, define main VC principles and aspects, and open to innovations in the field in order to prepare readers for adopting alternative space cooling solutions able in connecting climate and comfort issues to reduce energy consumptions and face one of the biggest challenges of our time: cooling spaces and providing user comfort in a heating world.

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Part I
Boundaries

Chapter 2
Ventilative Cooling Principles, Potential and Barriers

Per Heiselberg

Abstract This chapter introduces the main principles of ventilative cooling and the key performance indicators (KPI) to evaluate performance. It also presents and discusses the application potential and limitations as well as includes a critical discussion of barriers to ventilative cooling usage. The chapter is based on the outcome of the international research Annex 62—Ventilative Cooling developed under the Energy in Buildings and Communities (EBC) Programme of the International Energy Agency (IEA).

2.1 Ventilative Cooling Principles

Ventilative Cooling (VC) can be defined as the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment.

Ventilative Cooling utilizes the cooling and thermal perception potential of cool outdoor air and the air driving force can be either natural, mechanical or a combination of the two. The most common technique is the use of increased daytime ventilation airflow rates and/or night-time ventilation.

There is a wide range of ventilative cooling principles, and their application depends on climate and microclimate, building type, ventilation approach and user expectations. Ventilative cooling can be combined with other natural cooling solutions utilizing other natural heat sinks in the environment or with mechanical cooling solutions under unfavourable weather conditions.

Ventilative cooling principles for different outdoor climatic conditions and building ventilation systems are summarized in Table 2.1.

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Table 2.1 Overview of typical ventilative cooling strategies applied depending on outdoor climatic conditions and type of ventilation system [1]

Temperature difference[a]	Ventilative cooling	Supplementary cooling options
Cold (ΔT more than 10 °C)	Minimize air flow rate—draught free air supply	–
Temperate (2–10 °C lower than comfort zone)	Increasing air flow rate from minimum to maximum	Strategies for enhancement of natural driving forces to increase air flow rates Natural cooling strategies like evaporative cooling, earth to air heat exchange to reduce air intake temperature during daytime
Hot and dry (ΔT between − 2 and +2 °C)	Minimum air flow rate during daytime Maximum air flow rate during nighttime	Natural cooling strategies like evaporative cooling, earth to air heat exchange, thermal mass and PCM storage to reduce air intake temperature during daytime Mechanical cooling strategies like ground source heat pump, mechanical cooling
Hot and humid	Natural or mechanical ventilation should provide minimum outdoor air supply	Mechanical cooling/dehumidification

[a]Temperature difference between indoor comfort temperature and mean outdoor air temperature

2.1.1 Ventilative Cooling During Cold Outdoor Conditions

In wintertime when the outdoor air temperature can be very cold, the main challenge is to introduce outdoor air to the space without creating a high risk of draught and with a minimum use of electricity use for air transport.

For ventilation systems driven by natural forces, another challenge is the balance between required air flow rate to ensure an acceptable indoor air quality and to remove the excess heat load. If the heat load in the building is relatively small, the required air flow rate for indoor air quality might re-move more heat than needed. This will increase the heating system energy use, as effective heat recovery is difficult to be applied to naturally driven systems. Accurate control of the air flow rate is important to minimize the energy use for heating. The system should only be implemented, if the additional energy use for heating in winter associated with natural ventilation is compensated by larger energy savings in the rest of the year. Spaces in buildings with internal heat loads of more than 30 W/m^2 will typically benefit from natural ventilation.

For mechanically driven ventilation systems, the main challenge in exploiting outdoor air for cooling is to minimize the energy use for air transport. Typical mechanical systems cannot provide cold outdoor air to the building without increasing the risk of draught of the occupants. Supply air temperature is therefore increased by efficient heat recovery. This reduction in cooling capacity is compensated by an increased air flow rate up to 4–5 times the required for indoor air quality purposes. Increased pressure loss for heat recovery and in the air distribution system, increases the energy use for air transport considerably and in some cases outweighs the benefit of the “free cooling capacity” of the outdoor air. Solutions that can provide low temperature air supply without creating a draught risk for the occupants are therefore essential for mechanical ventilation system, especially in winter.

2.1.2 Ventilative Cooling During Temperate Outdoor Conditions

Under temperate conditions, outdoor air can be provided to the building and the occupied zone without creating a risk of draught. The air flow rate should be controlled according to the temperature and will typically be higher than required to ensure an acceptable indoor air quality. As in naturally driven systems there is no energy use for heating, cooling or air transport, the control requirements for the air flow rate are not very strict and technically relatively simple systems (like manual or automatic window opening in the façade) can handle the ventilative cooling appropriately. However, in periods with small temperature differences between indoor and outdoor air, where the naturally driving buoyancy forces are limited, it might be necessary to enhance them by implementing additional technical solutions to the building. In windy climates, solutions that can enhance wind forces are typically suitable (wind catchers, high positioned roof openings, etc.), while in sunny climates enhancement of buoyancy forces by solar chimneys might be useful.

For mechanically driven system, the cooling capacity can be kept constant at increasing outdoor air temperature by reducing the heat recovery efficiency. Not until outdoor air temperatures is above 18–19 °C, the cooling capacity will drop as increase in air flow rates is not possible or only to a very limited extend.

To enhance the ventilative cooling capacity, it is important to position the air intakes in a cool environment (shaded side of the building). It might also be necessary to further reduce the outdoor air intake temperature by supplementary natural cooling solutions like ground cooling (earth to air heat exchange) or evaporative cooling.

2.1.3 Ventilative Cooling During Hot Outdoor Conditions

In summer, in dry climates with high outdoor air temperatures during day-time, the air flow rates should be controlled to a minimum to ensure an acceptable indoor air quality and minimum additional heat load on the building. Effective night-time ventilation should be applied to remove the absorbed heat during daytime by cooling the building thermal mass. If the night-time cooling capacity is high enough and the building is well-designed with well-balanced glass area in the facades, efficient solar shading and exposed thermal mass, the next day's indoor temperature profile will be lower than outdoor temperature. Otherwise, supplementary natural cooling solutions and/or mechanical cooling will be required to reduce daytime outdoor air in-take temperatures in the warmest periods.

In hot and humid climates, naturally driven ventilative cooling will not be useful in the warm period. Mechanical ventilation systems are required to be supplemented by mechanical cooling to ensure a constant high cooling capacity regardless of the outdoor temperature and humidity.

2.1.4 Application of Hybrid Solutions

As aforementioned, adopting naturally or mechanically driven ventilation systems for ventilative cooling presents different challenges.

Naturally driven ventilation systems are most effective in buildings with high heat loads in winter, in buildings with low heat loads in summer and in periods of the year where the outdoor temperatures are temperate, while mechanical systems are more suitable in buildings with relative low heat loads in winter, in buildings with high heat loads in summer and in periods of the year where the outdoor temperature is either very cold (utilization of heat recovery to decrease energy use) or very warm (mechanical cooling can be applied to ensure thermal comfort).

In many cases it can be beneficial from both an energy and a thermal comfort point of view to combine the two different types of ventilation systems to exploit their different strengths and avoid their weaknesses. The most appropriate strategy for the combination of systems will depend on the outdoor temperature (climate) as well as the building type and the overall cooling demand.

In cold climates, the typical combination is the use of mechanically driven ventilation in the winter season and naturally driven ventilation during intermediate and summer seasons. In temperate climates, naturally driven ventilation can be used during the whole year. In warm climates, naturally driven ventilation is used in the winter period, while mechanically driven ventilation is preferable in the rest of the year.

Different systems can also be used at different times of the day. Generally, mechanically driven ventilation is used during occupancy hours and naturally driven ventilation is activated at night-time to increase the cooling capacity at night.

2.2 Climatic Potential for Cooling During Nighttime

The climatic potential for the ventilative cooling of buildings by night-time ventilation in Europe is evaluated in [2]. A method was developed which is basically suitable for all building types, regardless of building-specific parameters. This was achieved by basing the approach solely on a building temperature variable within a temperature band given by summertime thermal comfort.

2.2.1 Definition of CCP

Degree-days or degree-hours methods are often used to characterise a climate's impact on the thermal behaviour of a building. The daily climatic cooling potential, CCP_d, was defined as degree-hours for the difference between building temperature, T_b and external air temperature, T_e (Fig. 2.1):

$$CCP_d = \sum_{t=t_i}^{t_f} m_{d,t}\left(T_{b(d,t)} - T_{e(d,t)}\right) \quad \begin{cases} m = 1h & if \quad T_b - T_e \geq \Delta T_{crit} \\ m = 0 & if \quad T_b - T_e < \Delta T_{crit} \end{cases} \tag{2.1}$$

where t stands for the time of day, with $t \in \{0, \ldots, 24\ h\}$; t_i and t_f denote the initial and the final time of night-time ventilation, and ΔT_{crit} is the threshold value of the temperature difference, when night-time ventilation is applied. In the numerical analysis, it was assumed that night-time ventilation starts at $t_i = 19$ h and ends at $t_f = 7$ h. As a certain temperature difference is needed for effective convection, night ventilation is only applied if the difference between building temperature and external temperature is >3 K.

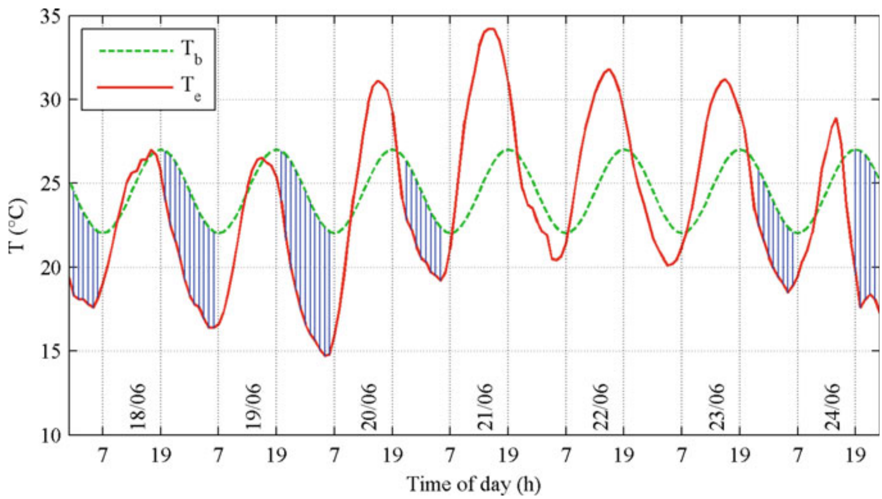

Fig. 2.1 Building temperature, T_b and external air temperature, T_e during one week in summer 2003 for Zurich SMA (ANETZ data). Shaded areas illustrate graphically the climatic cooling potential, CCP [2]

As heat gains and night-time ventilation are not simultaneous, energy storage is an integral part of the concept. In the case of sensible energy storage, this is associated with a variable temperature of the building structure. This aspect is included in the model by defining the building temperature as a harmonic oscillation around 24.5 °C with amplitude of 2.5 K:

$$T_{b(t)} = 24.5 + 2.5cos\left(2\pi \frac{t - t_i}{24}\right) \tag{2.2}$$

The maximum building temperature occurs at the starting time of night ventilation, and given a ventilation time of 12 h, the minimum building temperature occurs at the end time (Fig. 2.1). The temperature range $T_b = 24.5$ °C ± 2.5 °C corresponds to that recommended for thermal comfort in offices [3].

2.2.2 Practical Significance of CCP

To discuss the practical significance of the calculated degree-hours, an example shall be given. It is assumed that the thermal capacity of the building mass is sufficiently high and therefore does not limit the heat storage process. If the building is in the same state after each 24 h cycle, the daily heat gains Qd(Wh) stored to the thermal mass, equal the heat which is discharged by night ventilation:

$$Q_d = \dot{m} \cdot c_p \cdot CCP_d \tag{2.3}$$

The effective mass flow rate is written as $\dot{m} = A_{Floor} * H * \eta * ACR * \rho$, where A_{Floor} is the floor area [m^2] and H the height of the room [m], ACR the air change rate [h^{-1}] and η a temperature efficiency, which is defined as $\eta = (T_{out} - T_e)/(T_b - T_e)$ and takes into account the fact that the temperature of the outflowing air T_{out} is lower than the building temperature T_b. The density and the specific heat of the air are taken as $\rho = 1.2$ kg/m^3 and $c_p = 1000$ J/(kg K). Assuming a room height of H = 2.5 m and a constant effective air change rate of $\eta * ACR = 6$ h^{-1} yields:

$$\begin{aligned} \frac{Q_d}{A_{floor}} &= H \cdot \eta \cdot ACR \cdot \rho \cdot c_p \cdot CCP_d \\ &= \frac{2.5\text{ m} \cdot 6\text{ h}^{-1} \cdot 1.2\text{ kg/m}^3 \cdot 1000\text{ J/kg K}}{3600\text{ s/h}} CCP_d = 5 \frac{W}{m^2 K} CCP_d \end{aligned} \tag{2.4}$$

For the climatic cooling potential needed to discharge internal heat gains of 20 W/m^{2}K and solar gains of 30 W/m^{2}K during an occupancy time of 8 h follows:

$$CCP_d = \frac{Q_d}{A_{floor}} / 5 \frac{W}{m^2 K} = \frac{(20 + 30) \cdot 8}{5} \text{kh} = 80 \text{ kh} \tag{2.5}$$

This example should be seen as a rough estimation only, as solar and internal gains of an office room can vary substantially depending on the type of building use, local climate, and the solar energy transmittance and orientation of the façade.

2.2.3 Nighttime Cooling Potential

The degree-hour method was applied for a systematic analysis of the potential for nighttime cooling in different climatic zones of Europe. Semi-synthetic climate data [4] from 259 weather stations was used to map the cumulative frequency distribution of CCP for 20 European locations (Fig. 2.2). These charts show the number of nights per year when CCP exceeds a certain value.

In the whole of Northern Europe (including the British Isles) a very significant climatic cooling potential was found, and therefore passive cooling of buildings by night-time ventilation seems to be applicable in most cases. In Central, Eastern and even in some regions of Southern Europe, the climatic cooling potential is still significant, but due to the inherent stochastic properties of weather patterns, series of warmer nights can occur at some locations, where passive cooling by night-time ventilation might not be sufficient to guarantee thermal comfort. If lower thermal comfort levels are not accepted during short periods of time, additional cooling systems are required. In regions such as southern Spain, Italy and Greece climatic cooling potential is limited and night cooling alone might not be sufficient to provide good thermal comfort during all the year. Nevertheless, night-time ventilation can be used in hybrid cooling systems during spring and fall.

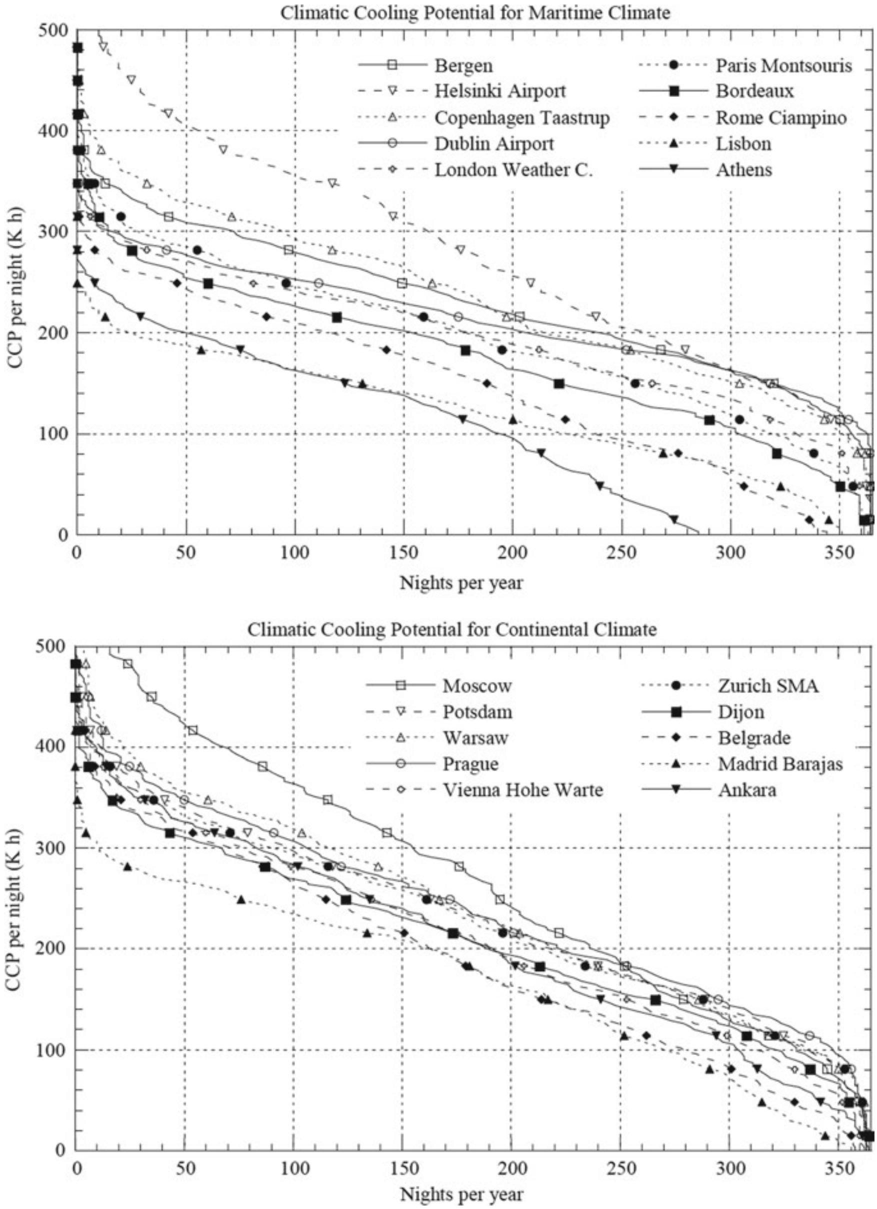

Fig. 2.2 Cumulative frequency distribution of CCP for maritime (top) and continental (bottom) locations [2]

2.3 Simplified Tool for Prediction of Ventilative Cooling Potential

Ventilative cooling is dependent on the availability of suitable external conditions to provide cooling. As buildings with different use patterns, envelope characteristics and internal loads level react differently to the external climate condition, the ventilative cooling potential analysis cannot abstract from building characteristics and use. In an assessment of the potential it is important to limit the evaluation of the cooling potential to the period where cooling is needed. Therefore, it is necessary, to look at the outdoor climate as well as the expected cooling need of the building.

A ventilative cooling potential tool (VC Tool) was developed within the Annex 62 project with the aim to assess the potential effectiveness of ventilative cooling strategies by taking into account building envelope thermal properties, occupancy patterns, internal gains and ventilation needs. It has to be considered only as a preliminary analysis on the assumption that the thermal capacity of the building mass is sufficiently high and therefore does not limit the heat storage process.

The ventilative cooling potential tool refers to the method proposed in [5] and is further developed within the IEA EBC Annex 62 activities [1].

This method derives from the energy balance of a well-mixed single-zone delimited by heat transfer surfaces. It assumes that a heating balance point outdoor air temperature can be determined below which heating must be provided to maintain indoor air temperatures at a defined internal heating set point temperature. Therefore, when outdoor dry bulb temperature exceeds the heating balance point temperature, direct ventilation is considered useful to maintain indoor conditions within the comfort zone. At or below the heating balance point temperature, ventilative cooling is no longer useful but heat recovery ventilation should be used to meet minimum air change rates for indoor air quality control and reduce heat losses.

This relies on the assumption that the accumulation term of the energy balance is negligible. It is a reasonable assumption if either the thermal mass of the zone is negligibly small or the indoor temperature is regulated to be relatively constant. Under these conditions, the energy balance of the zone is steady-state and can provide an approximate measure to characterize the ventilative cooling potential of a climate [5].

The analysis is based on a single-zone thermal model applied to user-input weather data on hourly basis. For each hour of the annual climatic record of the given location, an algorithm splits the total number of hours when the building is occupied into the following groups:

Ventilative Cooling mode [0]: when the outdoor temperature is below the heating balance point temperature, no ventilative cooling is required since heating is needed.

Ventilative Cooling mode [1]: Direct ventilation with airflow rate maintained at the minimum required for indoor air quality can potentially ensure thermal comfort when the outdoor temperature exceeds the balance point temperature, yet it falls below the lower temperature limit of the comfort zone.

Ventilative Cooling mode [2]: Direct ventilative cooling with increased air-flow rate can potentially ensure comfort when the outdoor temperature is within the range of comfort zone temperatures. In this case, the tool calculates the airflow rate required to maintain the indoor air temperature within the comfort zone temperature ranges. Direct ventilative cooling is not considered useful if the temperature difference between indoor and outdoor is below 3 K.

Ventilative Cooling mode [3]: Direct evaporative cooling (DEC) can potentially ensure comfort even if direct ventilation alone is not useful because the outdoor temperature exceeds the upper temperature limit. The evaporative cooling potential is considered when the expected temperature of the treated air is within the upper operative temperature limit minus 3 K. The expected outlet temperature of a DEC system is calculated according to [6, 7]. Moreover, an indirect limitation on DEC potential to prevent too high relative humidity values is also included, fixing a maximum reference for the outdoor wet bulb temperature—see [7] for residential buildings and [8] for offices.

Ventilative Cooling mode [4]: Direct ventilative cooling is not useful when the outdoor temperature exceeds the upper temperature limit of the comfort zone. Furthermore, this limit is also overtaken from the expected DEC outlet temperature.

If direct ventilative cooling is not useful for more than an hour during the occupied time, the night-time climatic cooling potential (NCP) over the following night is evaluated using the method described in [2]. Night-time ventilation is calculated by assuming that the thermal capacity of the building mass is sufficiently high and therefore all the exceeding internal gains can be stored in the building mass. Night-time cooling potential (NCP) over the following night is evaluated as the internal gains that may be offset for a nominal night-time air change rate.

Figure 2.3 shows as an example a prediction with the tool of the ventilative cooling potential for a building divided into the different ventilative cooling modes as well as the required flow rate.

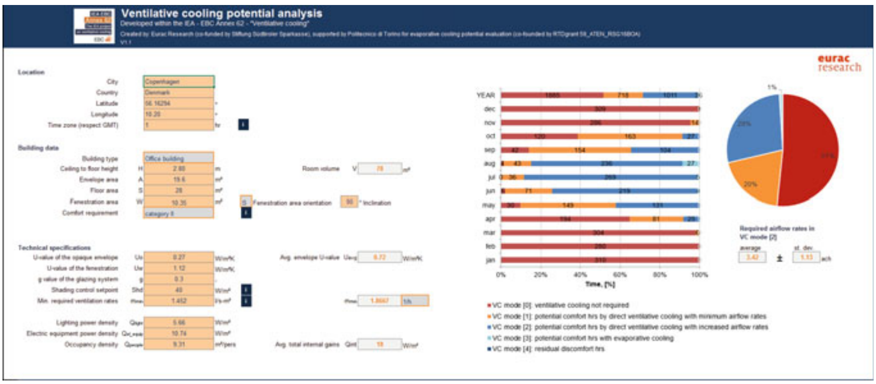

Fig. 2.3 Ventilative cooling potential and required air flow rate for a building predicted by the VC tool [1]

2.4 Simplified Method for Calculation of Opening Areas

The opening area in the building required to deliver the ventilative cooling air flow rate depend on the outdoor conditions and the position of the openings, i.e. the ventilation strategy applied.

2.4.1 Single-Sided Ventilation

In a single-sided ventilation strategy with only one opening used for ventilative cooling the necessary opening area can with reference to EN 16798-7:2017, [9] be calculated as:

$$A_{eff,e} = \frac{2 \cdot q_v}{1000\sqrt{maks\left(C_v \cdot v_{ref}^2; C_{t,e} \cdot h_v \cdot abs(t_i - t_u)\right)}} \tag{2.6}$$

where

$A_{eff,\,e}$ is the effective opening area for single sided ventilation (m^2/m^2 floor area)

q_v is the air flow rate (l/s m^2 floor area)

C_v is coefficient taking into account wind speed in airing calculations = 0.001 (1/(m/s))

$C_{t,e}$ is coefficient taking into account stack effect in airing calculations = 0.0035 ((m/s)/(mK))

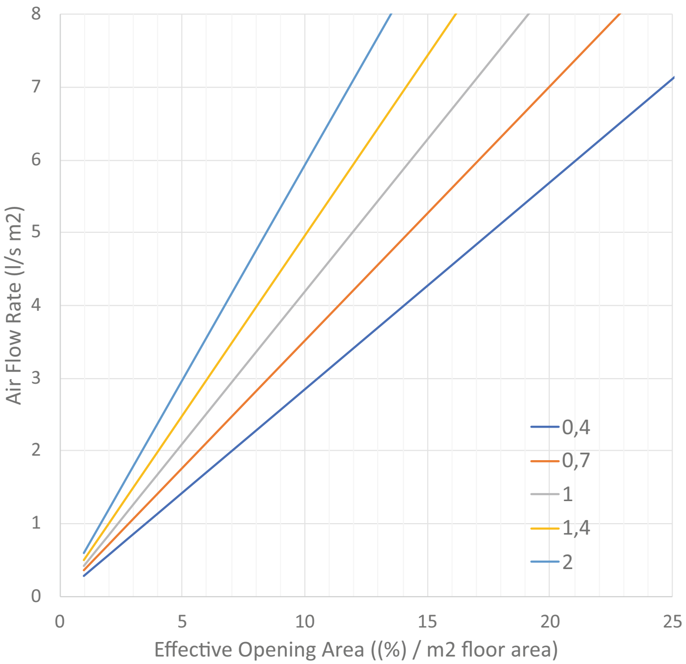

Fig. 2.4 Example of air flow rate per m^2 floor area for single-sided ventilative cooling as a function of opening area for different opening heights under the conditions $\Delta T = 2$ °C and $v_{ref} = 1.8$ m/s

v_{ref} is reference wind speed in 10 m height (m/s)
h_v is opening height (m)
t_i is indoor temperature (K)
t_u is outdoor temperature (K)

Figure 2.4 illustrates an example of its use. Opening height is very important for the necessary opening area.

2.4.2 *Stack Ventilation*

In a stack ventilation strategy with multiple openings positioned in two different heights in the same facade, the necessary opening area for ventilative cooling can with reference to [10] be calculated as:

$$A_{eff,o} = \frac{q_v}{1000\sqrt{C_{t,o} \cdot h_{st} \cdot abs(t_i - t_u)}} \tag{2.7}$$

where

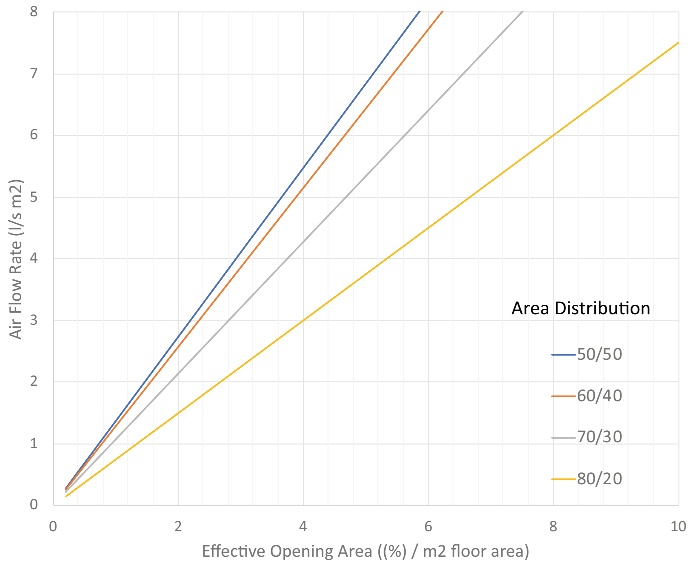

Fig. 2.5 Example of air flow rate per m^2 *floor area for stack ventilation as a function o*f opening area and for different relative distribution of the area between openings under the condition $\Delta T =$ 2 °C and $h_{st} = 3.0$ m

$A_{eff,\,o}$ is the effective opening area for stack ventilation (m^2/m^2 floor area)
q_v is the air flow rate (l/s m^2 floor area)
$C_{t,o}$ is coefficient taking into account stack effect in airing calculations = 0.025 ((m/s)/(mK))
h_{st} is the effective height for stack ventilation (m)
t_i is indoor temperature (K)
t_u is outdoor temperature (K)

The effective height for stack ventilation, h_{st}, can be found as the height difference between the middle of the top and bottom opening, respectively. The necessary opening area will depend on the distribution of the area between the openings in the two different heights, see Fig. 2.5.

2.4.3 Cross Ventilation

In a cross-ventilation strategy with several openings in different facades the necessary opening area can with reference to EN 16798-7:2017, [9] be calculated as:

$$A_{eff,v} = \frac{q_v}{1000 \cdot C_D \cdot v_{ref}\sqrt{\Delta C_p}} \quad (2.8)$$

where

$A_{eff,\,v}$ is the effective opening area for cross ventilation (m^2/m^2 floor area)

q_v is the air flow rate (l/s m^2 floor area)

C_D is a discharge coefficient for air flow through an opening = 0.60 (−)

v_{ref} is reference windspeed in 10 m height (m/s)

ΔC_p is the difference in wind pressure between different opening orientations (−)

The necessary opening area will depend on how the opening area is distributed on the different openings in the different façade orientations. EN16798-7:2017 includes a detailed methodology for calculation of the effective opening area for cross ventilation. A minimum opening area was obtained when the opening area is divided equally between openings (Fig. 2.6).

2.5 Key Performance Indicators

Key Performance Indicators (KPIs) are quantifiable measures used to evaluate design goals and to provide means for the measurement and monitoring of the progress of the design towards those goals. In IEA EBC Annex 62 national experts have discussed and developed KPIs to represent the performance of ventilation cooling [1].

2.5.1 Thermal Comfort

Thermal comfort performance cannot be represented well by a single indicator [11]. A set of indicators is needed. The standard EN 15251:2007 proposes methods for long-term evaluation of general thermal comfort conditions, where the combination of the “Percentage Outside the Range Index” (method A) and the “Degree-hours Criterion” (method B) enable the evaluation of both frequency and severity of overheating and overcooling occurrences. The reference comfort temperature can be derived from the Fanger model or the adaptive comfort model.

The Percentage Outside the Range (POR) index [%] calculates the percentage of occupied hours, when the PMV (Predicted Mean Vote) or the operative temperature is outside a specified range.

$$POR = \frac{\sum_{i=1}^{Oh} (wf_i \cdot h_i)}{\sum_{i=1}^{Oh} h_i} \tag{2.9}$$

where wf is a weighting factor which depends on the comfort range.

The comfort range can be expressed in terms of PMV, when referring to the Fanger model or in terms of operative temperature, when referring to the adaptive comfort model.

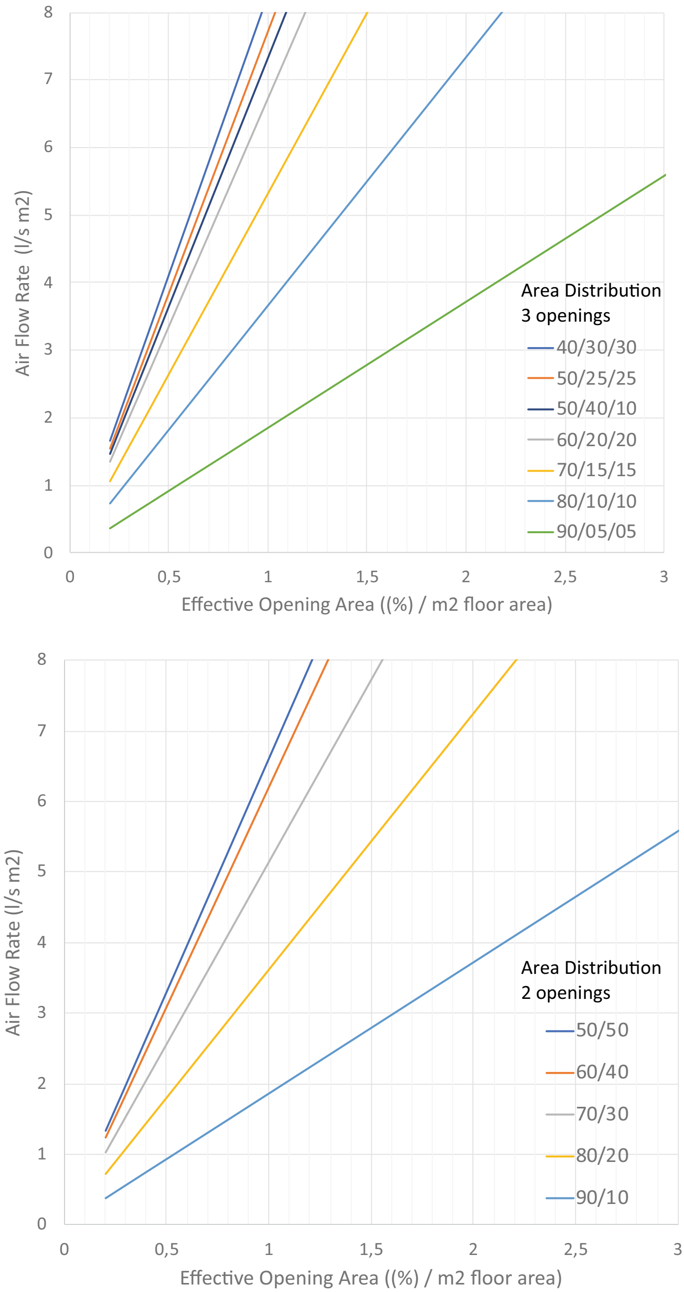

Fig. 2.6 Example of air flow rate per m^2 floor area for cross ventilation as a function of opening area under the condition of $v_{ref} = 1.8$ m/s, $\Delta Cp = 0.75$), when the opening area is distributed on two or three openings, respectively

According to the Degree-hours criterion (DhC) the time during which the actual operative temperature exceeds the specified range during the occupied hours is weighted by a factor which is a function of how many degrees the range has been exceeded.

$$DhC = \sum_{i=1}^{Oh} (wf_i \cdot h_i) \tag{2.10}$$

where weighting factor wf is here calculated as the module of the difference between actual or calculated operative temperature, θ_{op}, at a certain hour, and the lower or upper limit, $\theta_{op,limit}$, of a specified comfort range.

In case the comfort range is expressed in terms of PMV, the comfort operative temperature range has to be estimated by making assumptions on clothing and metabolic activity.

In case of compliance demonstration, it is recommended to use a concise indicator able to summarize the building performance in terms of thermal comfort. Previous studies [12], identified the long-term percentage of dissatisfied (LPD) index [%] as the optimal index to evaluate comfort conditions.

$$LPD(LD) = \frac{\sum_{t=1}^{T} \sum_{z=1}^{Z} \left(p_{z,t} \cdot LD_{z,t} \cdot h_t\right)}{\sum_{t=1}^{T} \sum_{z=1}^{Z} \left(p_{z,t} \cdot h_t\right)} \tag{2.11}$$

where t is the counter for the time step of the calculation period, T is the last progressive time step of the calculation period, z is the counter for the zones of a building, Z is the total number of the zones, $p_{z,t}$ is the zone occupation rate at a certain time step, $LD_{z,t}$ is the *Likelihood of dissatisfied* inside a certain zone at a certain time step and h_t is the duration of a calculation time step (e.g., one hour).

The Likelihood of dissatisfied can be formulated in different ways depending on the reference comfort model [12]. This indicator is concise, symmetric, robust and can be derived from building energy simulation outputs or long-term monitoring and can be used to compare the performance of different buildings as it is expressed in terms of percentage.

2.5.2 Energy

Existing energy indicators suit to all building typologies and evaluate active systems only. Energy indicators only implicitly consider the benefits of passive solutions, as energy need reduction, or the side effects, as the increase of heating need due to cold draughts or higher infiltrations or the increase of auxiliary energy consumption for control and automation. Passive systems are implicitly taken into account in the energy need calculation, but the related energy savings are not explicitly shown.

These calculation methods do not allow fair comparison between passive and active design options and other competitive measures.

Furthermore, most of the existing indicators consider either cooling or ventilation energy use, but not the total energy use for cooling and ventilation. Free cooling is meant to reduce or to avoid active cooling. Energy consumption of the fans is used to reduce or substitute the active cooling energy. The energy use for hygienic ventilation is usually not disaggregated from the overall energy consumption for ventilation.

From these considerations arose the need for an energy indicator or a set of indicators able to tackle the following aspects:

cooling need and/or energy savings related to ventilative cooling;
ventilation need and/or savings related to ventilative cooling only, possibly excluding the energy needed by hygienic ventilation;
possible drawbacks on energy behaviour during heating season, i.e. increase of heating need due to cold draughts or higher infiltrations, auxiliary energy consumption for control and automation;
ventilative cooling effectiveness as the match of cooling need and ventilative cooling potential.

In IEA EBC Annex 62 a new set of energy indicators was developed and tested for the evaluation of ventilative cooling system performances [1]. These are presented in the following.

The first indicator, the Specific Primary Energy Consumption of a ventilative cooling system, is meant to express the primary energy consumed by the ventilative cooling system per heated floor area.

$$Q_{pe,vc} = Q_{pe,v} + Q_{pe,h} + Q_{pe,c} - Q_{pe,v\_hyg} \tag{2.12}$$

where $Q_{pe,v}$ is the annual primary energy consumption of the fan, $Q_{pe,h}$ and $Q_{pe,c}$ are the annual primary energy consumption for space heating and cooling respectively and Q_{pe,v_hyg} is the annual primary energy consumption of the fan when operating for hygienic ventilation.

The second indicator, the Cooling Requirements Reduction (CRR), is meant to express the percentage of reduction of the cooling demand of a scenario in respect to the cooling demand of the reference scenario. It can be easily calculated by post processing outcomes of building energy simulation runs of a reference scenario (e.g. mechanically cooled building) and a ventilative cooling scenario (e.g. natural night cooling and daytime mechanical cooling). Therefore, it is particularly suitable to compare different design scenarios and drive design decisions.

$$CRR = \frac{Q_{t,c}^{ref} - Q_{t,c}^{scen}}{Q_{t,c}^{ref}} \tag{2.13}$$

where $Q_{t,c}^{ref}$ is the cooling demand of the reference scenario and $Q_{t,c}^{scen}$ is the cooling demand of the ventilative cooling scenario.

This indicator can range between −1 and +1. If CRR is positive, it means that the ventilative cooling system reduces the cooling need of the building. If CRR is equal to 1, the ventilative cooling scenario has no cooling requirement. If CRR is zero or negative, the ventilative cooling scenario does not reduce the cooling need of the building.

CRR can also be applied on a natural ventilation scenario, calculating the cooling need by means of dynamic energy simulations in ideal loads/unlimited power mode.

In the case of mechanical ventilation systems, it is worth noting that this indicator does not take into account the energy required for air distribution. Therefore, in case of mechanical ventilation, the design decision cannot be taken regardless of the ventilative cooling effectiveness, including fan energy use in the rating.

2.6 Critical Limitations and Barriers to Ventilative Cooling

2.6.1 Impact of Global Warming on Potential for Night-Time Ventilation

Global warming with increasing temperatures will have an impact on the potential for night cooling, [13] presents developed linear regression models to estimate the daily climatic cooling potential (CCP_d) from the minimum daily air temperature, T_{min}. For eight case study locations representing different climatic zones across a North–South transect in Europe, CCP was computed for present conditions (1961–1990) using measured T_{min} data from the European Climate Assessment (ECA) database. Possible future changes in CCP were assessed for the period 2071–2100 under the Intergovernmental Panel on Climate Change (IPCC) “A2” and “B2” scenarios for future emissions of greenhouse gases and aerosols defined in the Special Report on Emission Scenarios [14].

As an example Fig. 2.7 shows for Zurich and Madrid significant changes in the percentage of nights per season when the daily cooling potential, CCP_d exceeds a certain value. For Zurich, under current climate conditions CCP_d is higher than 80 Kh (roughly necessary to discharge heat gains of 50 W/m^2, see Sect. 2.2.2) throughout most of the year, except for about 10% of summer nights. Under the “A2” scenario CCP_d was found to fall below 80 Kh in more than 50% (“B2”: 45%) of summer nights.

For the studied locations in Southern Europe CCPd values under present climatic conditions were found to be below 80 Kh throughout almost the entire summer, but a considerable cooling potential was revealed in the transition seasons. For the whole year the percentage of nights when CCP_d exceeds 80 Kh in Madrid was found to decrease from 70% under present conditions to 52% under “A2” conditions, [13].

The decreases found in mean cooling potential have regionally varying implications. In Northern Europe the risk of thermal discomfort for buildings that use

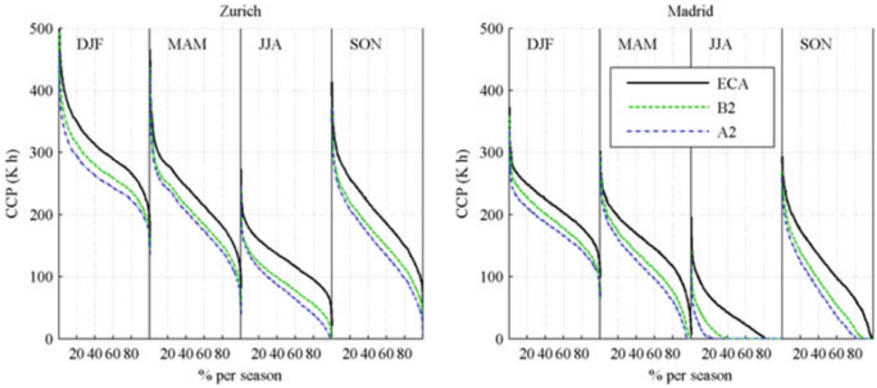

Fig. 2.7 Seasonal cumulative distributions of CCP_d in Zurich (left) and Madrid (right) for current climate (ECA) and averages for forcing scenarios “A2” and “B2” [13]

exclusively ventilative night cooling is expected to steadily increase up to possibly critical levels in the second half of the twenty-first century. In Central Europe extended periods with very low night cooling potential—where thermal comfort cannot be assured based on night-time ventilation only—could already become more frequent in the next few decades, if a strong warming scenario became real. For Southern Europe the potential for ventilative night cooling will sooner or later become negligible during summer and will decrease to critical levels in the transition seasons.

It should be noted that although cooling by night-time ventilation is expected to become increasingly ineffective during summer, it is likely to remain an attractive option in the transition seasons. This will be even more the case, if it is considered that under general warming the cooling season will tend to start earlier in spring and end later in autumn. In fact, the decreasing cooling potential and the simultaneously increasing cooling demand result in a shift of possible applications of night-time ventilation in Europe from South to North and from summer to the transition seasons.

Any assessment of possible changes in future climate is subject to large uncertainties. Nevertheless, the extent and rate of the expected climatic changes and the long service life of buildings imply the need for designing buildings capable of providing comfortable thermal conditions under more extreme climatic conditions.

2.6.2 Impact of Urban Environment (Heat Island and Reduced Natural Driving Forces)

The urban environment will have an impact on the ventilative cooling potential and also impose constraints for the use of natural driving forces. Urban environments have typically lower wind speeds, higher temperatures and higher noise and pollution levels [15].

In many cities the heat island effect with higher temperatures causes a decrease in the potential for ventilative cooling in the urban area compared to surrounding rural areas—where climate data usually originate. The CCP concept was applied to assess the implications of heat islands for night-time ventilative cooling [16]. A reduction in CCP during summer of about 9% was found for London Even larger effects were found for Adelaide, Australia (up to 26%) and Sde Boqer, Israel (up to 61%).

2.6.3 Outdoor Noise Levels

Outdoor noise levels in the urban environment can be a major barrier for application of ventilative cooling by natural driving forces and methods for estimating noise levels in urban canyons is needed to assess the potential as well as to assess the risk that occupants will close windows to keep out noise but also compromise the ventilative cooling strategy. In urban canyons the noise level increases with traffic density and decreases with height above the street at the attenuation increases with distance to the source. The attenuation decreases with increasing street width. Based on these relationships and measurements performed in 9 different urban canyons in Athens [17] developed a simple model calculating the direct as well as the reverberant noise component at a certain height above the street level. Calibration of the model with measurements showed that the noise attenuation was almost entirely a function of the street width and the height above the street. Making the assumption that traffic level is a function of the street width the noise level becomes purely a function of the street geometry.

In [17] a tolerable noise level in European offices was suggested to be around 60 dB. At the same time the noise attenuation at an open window is accepted as 10–15 dB. Thus an outdoor noise level of 70 dB or less is likely to be acceptable. Using special methods and window designs, a further 3–5 dB attenuation is possible. Figure 2.8 shows the expected noise levels in Athens at different street widths and heights above the street and the implications of this for use of the natural ventilative cooling potential at different heights above street level according the above rules of thumb.

2.6.4 Outdoor Air Pollution

Key outdoor pollutions like NO_2, SO_2, CO_2 O_3 and suspended particulate matter PM are usually measured continuously in larger urban environments and are often considered as a major barrier for application of natural ventilative cooling.

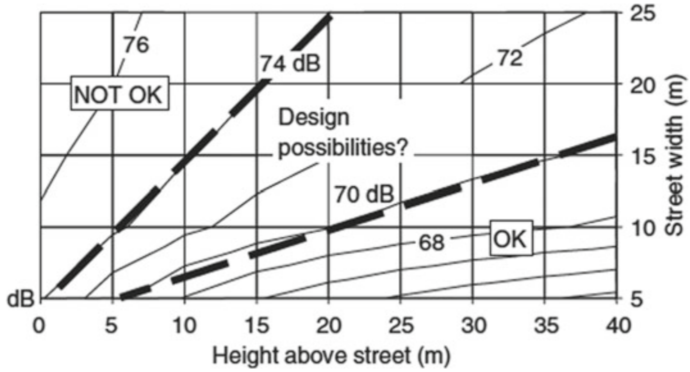

Fig. 2.8 Contours of noise level at different heights above the street and street widths. Configurations in which natural ventilation is possible are indicated (OK), as are those in which it is ruled out (NOT OK). Between these two extremes is a region in which there are possibilities for design solutions, [17]

The mean levels of SO_2 are equal outdoors and indoors, while NO_2 and O_3 reacts with the building materials resulting in a lower concentration indoors than outdoor for an airtight building. The transport of PM depends on the particle size. Estimation of the indoor/outdoor pollution ratio is the key to an assessment of the potential use of natural ventilative cooling in an urban environment.

In [15] the indoor/outdoor pollution ratio was reported in nine school buildings with different facade permeability, see Fig. 2.9.

In the experiments the indoor/outdoor (I/O) pollution ratio were studied for ozone, nitrogen dioxide and 15 sizes of PM. The ratio of indoor/outdoor concentration was

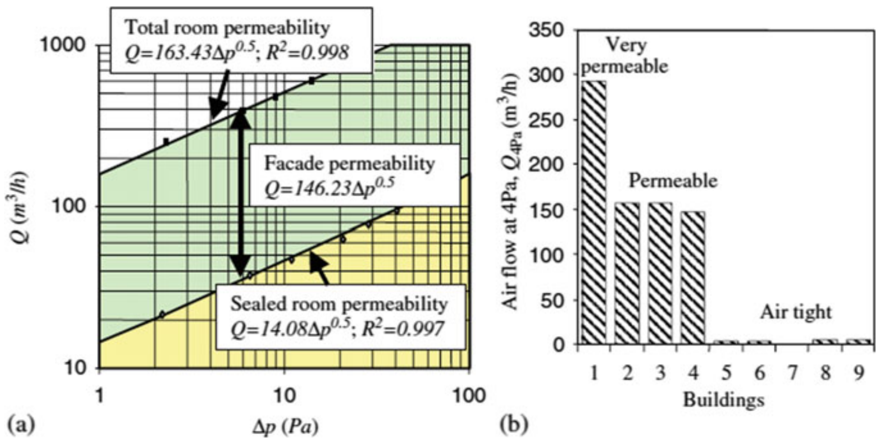

Fig. 2.9 Building permeability for nine school buildings used in experiments on indoor/outdoor pollution ratio ([15], original data from [18])

found to be a function of airflow through the façade (façade airtightness) and of the outdoor concentration. The indoor concentration was smaller inside than outside. Ozone presented the lowest I/O ratio (0.1–0.4), with higher I/O ratios measured for higher outdoor ozone concentration. The I/O ratio for nitrogen dioxide was between approximately 0 and 0.95 with lower values for higher outdoor concentration. The I/O ratio for PM depended on the particle size. The most important variation (0.25–0.70) was measured for particles of small size (0.3–0.4 mm); particles of larger size (0.8–3 mm) represented lower, but comparable, variation of the I/O ratio (0.3–0.7).

Acknowledgments The material presented in this chapter is based on the outcome of the international research project IEA EBC Annex 62 Ventilative Cooling and is the result of an international joint effort conducted in 15 countries. All those who have contributed to the project are gratefully acknowledged.

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Chapter 3
Ventilative Cooling and Comfort Models

Fergus Nicol

Abstract This chapter focuses on the description of comfort models for Ventilative Cooling. In particular, the adaptive comfort approach is described in full practical detail with an eye to related standards and regulations and designing buildings which will allow occupants to make themselves comfortable.

3.1 Chapter Introduction and Methodology

Thermal comfort in most standards and guidance is defined as *That* ***state of mind*** *that expresses satisfaction with the thermal environment (author emphasis),* but comfort is most often investigated as if it arises largely from a heat balance between metabolic heat production, and heat loss from the body surface. It is, of course, necessary to balance metabolic heat production and the heat loss, from the body over time, but the experience of comfort is also heavily influenced by other psychological, social and behavioural factors that impinge on a 'state of mind'.

Temperature is the physical measure which most clearly relates to thermal comfort, and the sensation involves both the temperature of the air (T_a) surrounding the body, and the radiant temperature in the occupied space (T_r). The operative temperature (T_{op}) is an index which combines the air temperature and the mean radiant temperature into a single value to express their joint effect. It is a weighted average of the two temperatures, the weighting depending on the heat transfer coefficients by convection (h_c) and by radiation (h_r) at the clothed surface of the occupant. It is often used to express the overall temperature in a space. Thus in both the ASHRAE 55 [1] and the BSI/CEN EN15251 [2] international standards, the neutral (or comfort) temperature in the adaptive section is expressed in terms of the operative temperature (see Nicol et al. [3], Chap. 5)

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The operative temperature is defined as:

$$T_{op} = H \cdot T_a + (1 - H) \cdot T_r \tag{3.1}$$

where H is the ratio $h_c/(h_c + h_r)$. Researchers have differed in their estimates of the values of these heat transfer coefficients, and hence of the value of H. In the CIBSE Guide A [4] the value $\sqrt{(10\ v)}$, is used for the ratio of h_c to h_r where v is the air speed, and so:

$$T_{op} = \frac{T_a \cdot \sqrt{10v} + T_r}{1 + \sqrt{10v}} \tag{3.2}$$

So the relative importance of radiant temperature and air temperature in the value of T_{op} is a function of the air velocity, At higher values of v, the operative temperature tends towards the value of the air temperature. At indoor air speeds below 0.1 m/s, natural convection around the human body is assumed to approach 0.1 m/s so T_{op} approximates to

$$T_{op} \approx 1/2\ T_a + 1/2\ T_r \tag{3.3}$$

Operative temperature is a theoretical and not an empirical measure and therefore cannot be measured directly, but in practice it approximates to the temperature of a 40 mm diameter globe thermometer.

Although the equations for the evaluation of Fanger's (1970) PMV/PPD (Predicted Percentage of Dissatisfied) [5] index do not use the operative temperature as a variable, the basic physical relationships shown in Eqs. (3.2) and (3.3) will apply in any indoor space, as will an approximation of the relationships shown in Eq. (3.2) and the role of air movement in them.

Evaporative heat loss is also determined partly by the air movement. The equations for evaporative heat loss are

$$E = wh_e(p_{ssk} - p_a) \tag{3.4}$$

where E is the rate of evaporative heat flow per square metre of body surface, w is the 'skin wettedness' (a measure of the proportion of the skin which is wet with sweat in the thermal, conditions) [6], h_e is the evaporative heat transfer coefficient (see below), p_{ssk} the saturated water vapour pressure at skin temperature (kPa), and $_{pa}$ the water vapour pressure of the air (kPa).

$$h_e = 16.5 h_c\ (\mathrm{W/m^2kPa}) \tag{3.5}$$

The cooling effect of air movement on wetted skin is clearly considerably greater than that on dry skin—an effect which will be familiar to anyone who has used a blown air hand-dryer. The driving force for the heat loss is therefore related to the difference between the water vapour pressure at the temperature of the skin (or other wetted surface), and the water vapour pressure of the surrounding air, making the total heat loss from the body a combination of convective heat loss, radiative heat loss and evaporative heat loss.

So air movement is clearly an important factor in the thermal relationship between humans and their environment. Air movement influences both the heat loss from the surface of the body, and also the relative importance of radiant and convective heat exchange. Models of thermal comfort were based on achieving a heat balance between building occupants and their immediate environment. Many theoretical, or empirical, comfort models were developed to enable air conditioning engineers to design their cooling systems. At first the model assumed that the resulting indoor conditions were comfortable and air movement was a source of discomfort or draught. With increased interest in natural ventilation and adaptive behaviour, air movement is now also seen as a useful, free, source of comfort cooling. Although in cool conditions an increase in ventilative cooling can increase cold discomfort, and have a negative effect, in warm environments where it is heat that is causing discomfort, the cooling effect of air movement will help This can break down at extremely high environmental temperatures where heating by radiant and convective transfer becomes greater than the cooling by evaporation.

The cooling effect of air movement is influenced not only by the mean air speed but also by its variability through turbulence [7]. It is possible to apply dynamic airflows in work areas in warm conditions through proper dynamic air supply devices. Compared to constant mechanical airflow, dynamic airflows can act like real or simulated natural wind and can achieve stronger cooling effects and better thermal comfort sensations without negatively impacting occupants' work performance [8]. The effectiveness of fans for cooling can also be increased by incorporating evaporative cooling systems [9].

3.2 Principles of Adaptive Thermal Comfort

Based on observations in field surveys, the ***Adaptive Principal*** states that *If an environment is uncomfortable people will take actions to restore their comfort*. In the adaptive approach these actions can be physiological, and possibly psychological, but are principally behavioural. Analysis of the results of international comfort surveys in the field show that this results in a strong relationship between neutral temperature of a group of people, and the mean indoor temperature they are experiencing. In naturally ventilated buildings in 'free running' mode (i.e. without heating or cooling), the indoor temperature will follow the outdoor temperature as modified by the building's form and physical character. These two relationships imply a relationship between the indoor comfort temperature, and the outdoor temperature. This is the relationship which is most widely used in international 'adaptive' comfort standards.

3.2.1 Adaptive Comfort in Free-Running Naturally Ventilated Buildings

The neutral (or comfort) temperature is the temperature which at which a vote of ‘neutral’ (0) is most likely to be cast by the subjects in a field survey. Actual comfort temperatures can only be found from the results of comfort surveys in which the comfort votes are collected. Comfort votes can be named +3 Hot, +2Warm, +1 Slightly warm, 0 Neutral, −1 Slightly cool, −2 Cool, −3 Cold. This scale is known as the ASHRAE scale and is used in most comfort surveys. Figure 3.1 shows the result of plotting the neutral temperature against the prevailing outdoor temperature for a wide range of buildings in free-running mode. The ‘outdoor prevailing temperature’ is the typical outdoor temperature at the time of the survey. In the ASHRAE and CEN standards this is the running mean of the daily mean outdoor temperature or a weighted mean of the daily mean outdoor temperature over the last few days. All buildings in the survey are in free-running mode at the time of the survey.

In Fig. 3.1 each dot on the graph gives the mean neutral temperature and the concurrent mean outdoor temperature from a whole survey, including in some cases, hundreds of sets (and none <20) of individual votes and measurements of environmental variables (temperature indoors and out, humidity, air movement etc.). In some surveys the actions of building occupants have taken to make themselves comfortable have also been recorded.

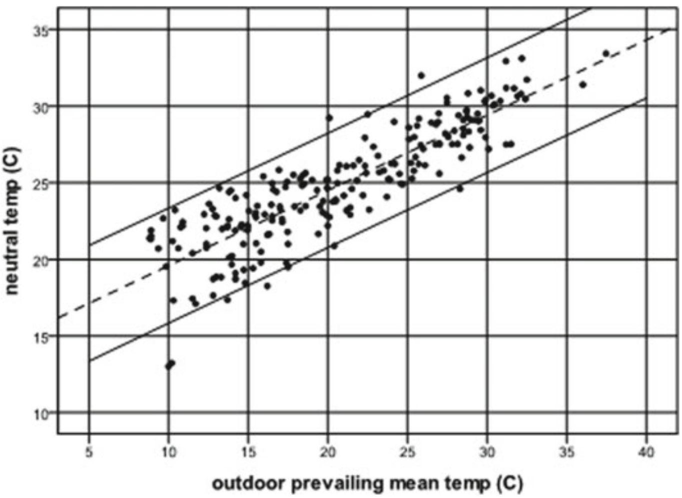

Fig. 3.1 The relationship between the temperature at which building occupants will be most likely to vote ‘neutral’ on the ASHRAE comfort scale and the outdoor temperature. In this graph all the buildings are in ‘free-running’ mode meaning that no mechanical heating or cooling is in operation at the time of the survey

The mean neutral temperature in Fig. 3.1 is 24.9 °C (s.d. 3.9 K) at the mean prevailing outdoor temperature of 21.3 °C (s.d. 8.5 K). The correlation coefficient between the neutral temperatures and the outdoor prevailing mean is 0.89, and the equation of the regression-line is:

$$T_n = 13.8 + 0.53(\pm 0.02)T_o \quad \text{(Humphreys et al. [12], Chap.29)} \tag{3.6}$$

Where T_n is the neutral indoor operative temperature, and T_o the prevailing mean outdoor temperature.

The scatter of the points about the line (the residual s.d.) is 1.8 K. The standard error associated with the estimate of a neutral temperature based on 20 observations was some 0.4 K. This is very much smaller than the observed scatter. It follows that the scatter of the points about the line is not attributable chiefly to random error, but represents real differences among the neutral temperatures of the various groups of people at any prevailing mean outdoor temperature. It is therefore better to represent the data not by a line, but by a band. The band drawn on the figure includes 95% of the observed neutral temperatures. The neutral temperatures in all the surveys selected (N $\geq$ 20) from the SCATs database [10], and from the ASHRAE RP-884 database [11], fall within the band (Fig. 3.1). The regression line should be interpreted as giving the most probable neutral temperature, rather than the only possible neutral temperature.

3.2.2 Adaptive Comfort in Conditioned Buildings

In international comfort standards [1, 2], and for much of the advice [4] given by the Heating, Ventilating and Air Conditioning (HVAC) industry, it is assumed that adaptative behaviour does not occur in buildings which are heated or cooled (conditioned), because the HVAC system provides ‘comfort’, making such behaviour unnecessary.

In fact, although the indoor temperatures in buildings which are conditioned (filled circles in Fig. 3.2) exhibit a smaller range, there is still a strong correlation between neutral temperature and mean indoor temperature. This suggests that even in conditioned indoor conditions building occupants adapt to be comfortable at temperatures close to the mean indoor temperature. As with free-running buildings, the occupant are effectively adjusting themselves to the conditions provided by the building, and its conditioning systems.

It is noticeable that in Fig. 3.2 that a large proportion of conditioned buildings (heated or cooled) have indoor temperatures (and neutral temperatures) in the range 20–25 °C (roughly the temperature range suggested for conditioned offices and homes in existing, non-adaptive, standards). In conditioned buildings the air-conditioning or other temperature control mechanisms will have been set to this temperature range. In Fig. 3.2 the mean indoor temperature in conditioned buildings is 23.8 °C (s.d. 1.7 K), and in naturally ventilated free running buildings 24.7 °C (s.d.

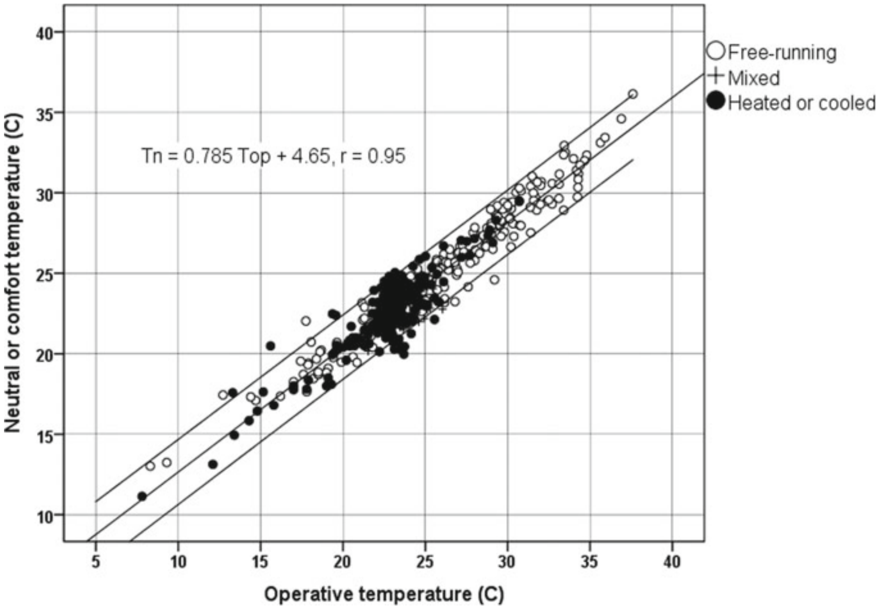

Fig. 3.2 The variation of comfort or neutral temperature (T_n) with the mean indoor operative temperature (T_{op}) in a large number of survey results (from Humphreys et al. [12])

5.0 K). Notice also that the neutral temperature is slightly below the mean operative temperature at high mean temperatures (i.e. they would prefer it to be a bit cooler) and slightly above it at low mean operative temperatures (they would prefer it to be a bit warmer), but the overall correlation between Operative and Neutral temperatures is 0.94 and the equation of the regression line is

$$T_n = 0.783 \cdot (\pm 0.011) \cdot T_{op} + 4.5 \quad \text{(Humphreys et al. [12], Chap.28)} \tag{3.7}$$

3.3 Air Movement as an Adaptive Opportunity in Buildings

Adaptive thermal comfort assumes that people who are uncomfortable are motivated to take the *opportunities which are available to them* to make themselves comfortable i.e. those which the building, its services and the culture of the building's occupants have made available to them. Culture can be hugely important in driving or limiting actions and culture here might refer to the cultural practices of the local population, or the building management, or the group around the occupant in question. Some of these *adaptive opportunities* enable people to use the effect of air movement (either mechanically created or through the thermal or pressure driven sources) to enable building occupants to adapt their indoor environment to their liking, or to influence their own neutral temperature to move towards the conditions in the building, by for instance taking off or putting on clothes, changing postures, activities or locations in a room or building.

Many of the technologies used rely on the provision of air movement. Air movement is relatively quick and easy to control and is often readily available through simple mechanical devices such as fans and windows. The use of fans in hot conditions to increase air movement is almost universal at certain temperatures.

3.3.1 Fans

A fan does not typically change the air temperature in a space, but it simply does two things:

(a) Increases or decreases air movement to enhance comfort by increasing convective and/or evaporative heat losses from the skin or reducing them. This function is commonly used in homes, offices and public spaces.
(b) Mixes the room air to change temperatures by drawing down warmer, more buoyant air to increase comfort nearer the floor in cooler spaces. This feature can be exploited with large ceiling fans in high industrial spaces and office atria to enhance the comfort of workers on the floor [7].
(c) If the fan pushes air over, or through a water body or moisturised air then its temperature will be lowered by evaporative cooling, a feature exploited in some new cool towers where the effect can be enhanced using micronized water jets spray droplets into the air at the top of a shaft, cooling the air that then drops, often assisted by a fan, to cool people at the base of the tower [9].

Pakistan is a country with a wide range of warm and cool climates from the typical south-asian composite climate in Islamabad to the cold desert of Quetta on the border of Afghanistan, and Saidu Sharif in the Himalayas or Multan in the hot desert of the Punjab and Karachi's warm humid coastal climate. Figure 3.3 illustrates the varying use of fans in these various cities in Pakistan and shows that fans are used across a very wide range of conditions, from as low as 18 up to 35 °C with differences in practice visible between the cooler climates to the very hot climates.

The use of Fans in European offices and other cooler climates will only be significant in warmer season. Their use in Quetta as shown in Fig. 3.3 illustrates the difference. Fans begin to be used at a similar temperature to hotter climates but then rises less steeply. This is often caused by there being some places where fans are not available, and consequently fewer being available for use.

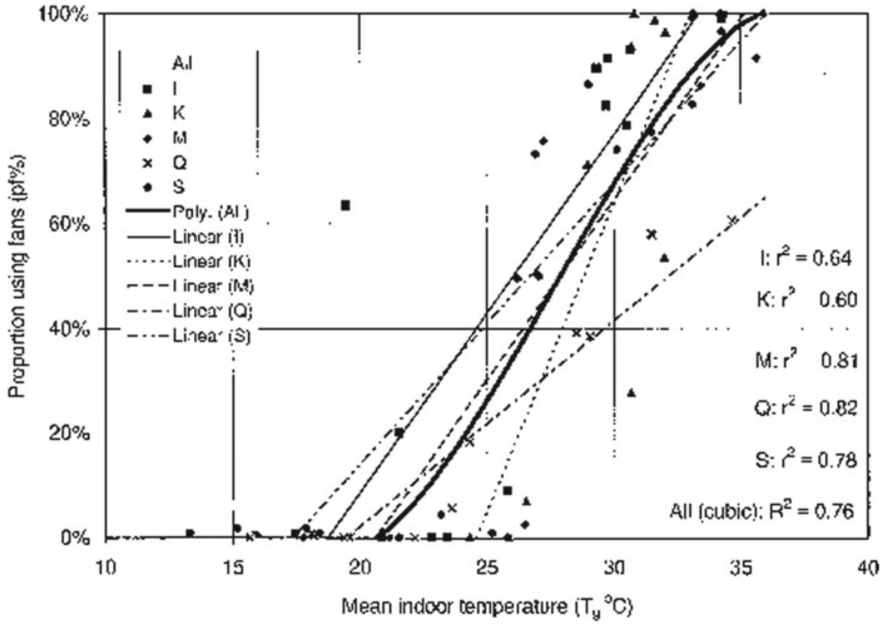

Fig. 3.3 Fans are widely used in hot climates to help offset the effects of high temperature (Date from offices in Pakistan. Nicol et al. [14]). The initial letters signify the city where the data were collected I = Islamabad, K = Karachi, M = Multan, Q = Quetta and S = Saidu Sharif

3.3.2 Windows

The opening of a window can change the indoor temperature, and it can also encourage indoor air movement which will modify the heat exchange at the body surface of the occupants so that their desired temperature is also changed.

The opening of a window will have a cooling effect, for any individual, at a temperature which might be called the 'warm trigger temperature' (t_{warm}, Fig. 3.4a).

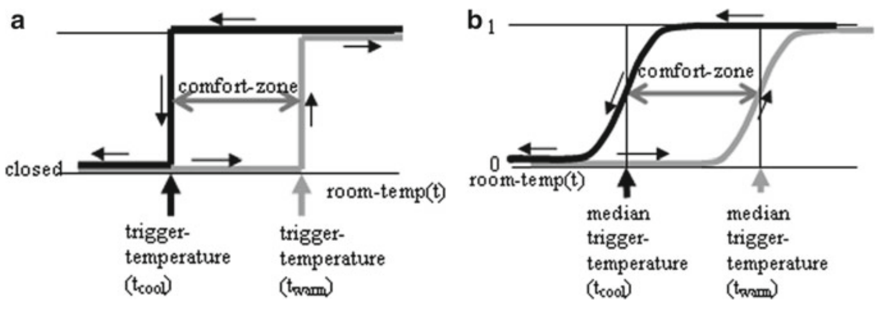

Fig. 3.4 **a** Showing the basic model for an individual, **b** the overall model for a group

The assumption is that opening the window will (a) allow cooler outdoor air to cool the interior, (b) increase air movement (the effect of outdoor wind or of thermal pressure). The overall cooling effect can be increased by air movement. Even if the outdoor air coming in through the window is at a higher temperature than the indoor air the increased loss of heat through evaporation can mean the indoor temperature feels cooler. Likewise, if the room becomes too cool and the window is open, the individual will close the window at a 'cool trigger temperature' (t_{cool} in Fig. 3.4a).

Figure 3.4b shows how this might apply to a group of people in a single room. Each will have a different pair of trigger temperatures and this will be expressed by a horizontal distribution. The median values of the trigger temperatures t_{warm} and t_{cool} are suggested. As temperatures vary within the room the likelihood of windows being open or closed will change but in general there will be a tendency for the windows to be open more often within a limiting envelope.

Figure 3.5 shown the distribution of the likely number of open windows in buildings at different indoor temperatures. Such a distribution curve can be used to estimate energy use and comfort in a group of buildings with opening windows [13]. The air movement measured in any building tends to rise as the temperature increases as a result of the adaptive behaviour of occupants in opening windows and using fans.

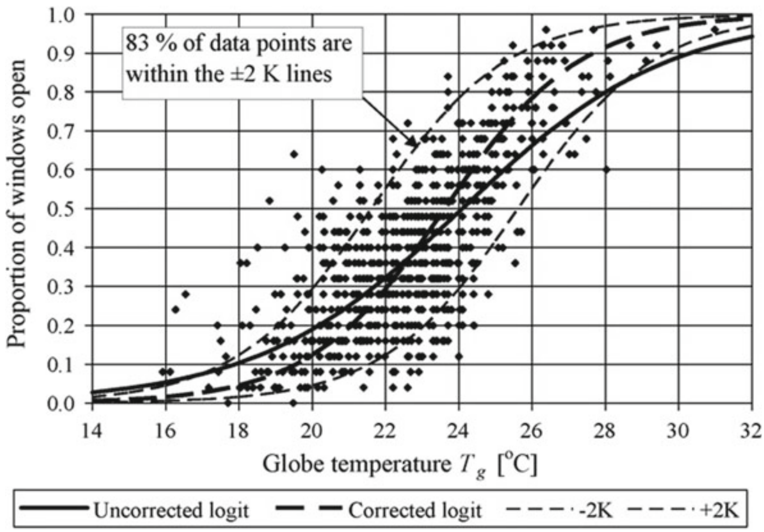

Fig. 3.5 The shape of the window open distribution in data collected from a number of buildings in the UK (Oxford and Aberdeen) over a year. Each point is the proportion of windows open from 25 occasions with the same indoor temperature (*Source* Rijal et al. [13])

3.3.3 Air Movement in Buildings

That air movement is used as a tool to cool the interior is amply illustrated by the two graphs in Fig. 3.6 which show the mean air speed in buildings as a function of indoor temperature in offices in Europe and Pakistan. Note the air speed is represented by its square root in these graphs because the square root best represents the cooling effect of air movement. Note also that the minimum air speed is represented by 0.3 $(m/s)^{½}$ ($\approx$0.1 ms^{-1}) which is the speed of air caused by convective heat lost at the skin. Note that air velocities are higher in the warmer climate but that in both the increase starts at about 26 °C.

The cooling effect of air movement through windows can be enhanced by encouraging cross ventilation between one opening and another. Air movement is managed in buildings not just through windows but that other pathways are also widely used. The opening of doors can create effective cooling, or warming, air pathways through a building, driven by temperature differences between spaces and wind pressure between openings. In a wide survey in the UK, Raja et al. [15] investigated the effect of having both door and window open and found temperature of the average room with cross ventilation was lower by about 1 °K than in those with one-sided ventilation at the same outdoor temperature.

Spaces such as atria, sunspaces and conservatories can act to 'pump' warmed, expanded, air through a building. Stair wells and vertical shafts can work to push warmer air upwards by buoyancy during warm spells, or draw cooler air downwards in cooler ones. Good designers can anticipate and use the form of the building and knowledge of the local climate to design internal comfort conditioning systems using such thermal and pressure driven air systems.

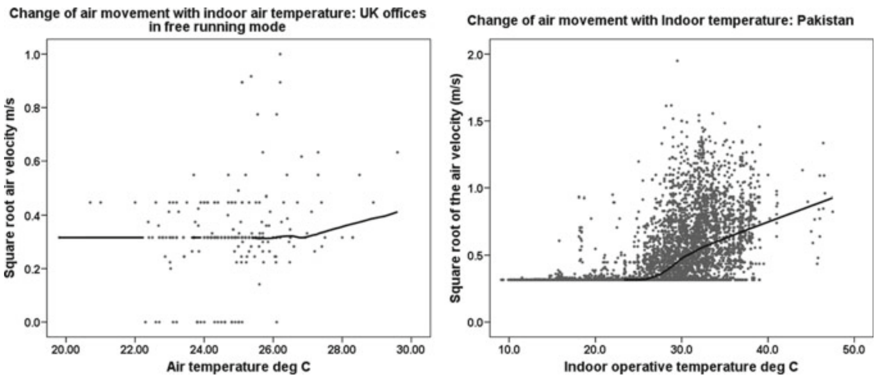

Fig. 3.6 Mean air movement measured at different indoor temperatures in (left) free-running European offices (data from France, Greece, Portugal and UK in the SCATs project) and (right) Pakistani offices (from various towns [14])

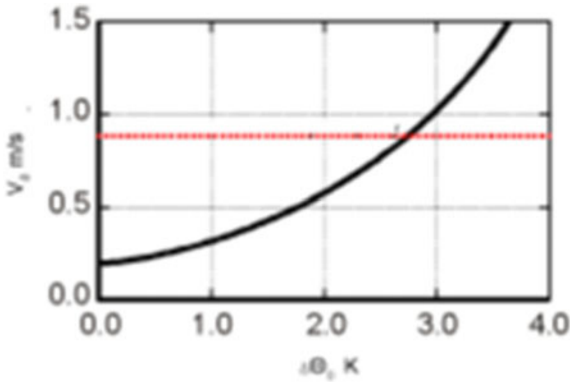

Fig. 3.7 Equivalence between air velocity and temperature as proposed by ASHRAE 55 [1] and BSI [2]

3.3.4 Air Movement in International Standards and Adaptation

As far as possible the indoor environment in a building should naturally fall within usual local comfort limits. This can be achieved not only with mechanical ventilation, but also in a more environmentally friendly and low energy way by using passive means to control temperatures indoors. These can use, for instance, permanent or temporary shading, thermal mass, orientation, window size, the diurnal and seasonal harvesting or dumping of heat with windows utilising local micro-climates, and so on. The building should allow occupants to control their environment with a range of adaptive opportunities including opening windows, adjustable shades to keep sun out, fans for increased air movement and different climate spaces around the building.

International Standards recognise the importance of air movement through a rough 'equivalence' between air movement and temperature reduction (Fig. 3.7). There is a growing imperative to mitigate climate change by reducing carbon dioxide emissions, hence reducing energy use in buildings and limiting the use of refrigerant gasses, particularly those with a high global warming potential. Thus the use of mechanical heating and/or cooling should be kept to a minimum by using careful building design which takes account of the regional climate and importantly local micro-climates around a building.

3.4 Building Occupants and Changing Temperatures

Nicol [16] found that in dwellings the range of indoor temperatures is often larger in buildings when they are heated or cooled than when they are free-running. This is not predicted by comfort standards where buildings with mechanical conditioning are

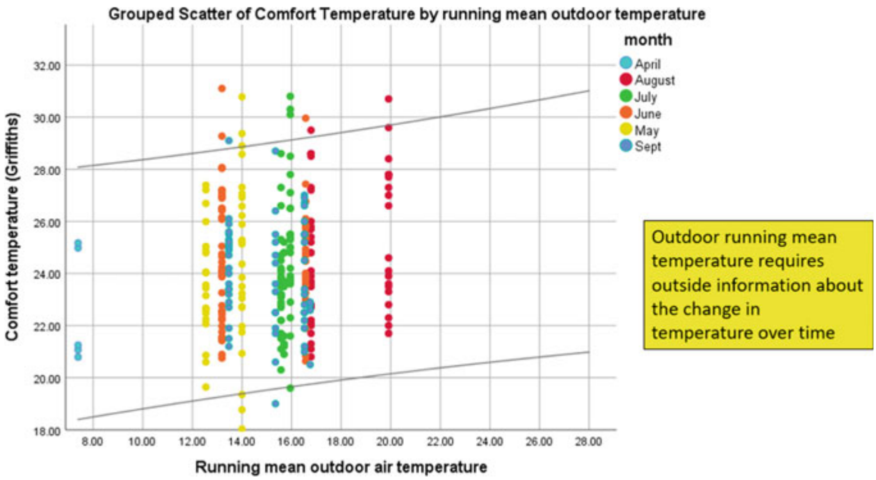

Fig. 3.8 Showing the wide range of indoor neutral (comfort) temperatures at monthly intervals

expected to be using the conditioning keep their temperature constant at a calculated neutral temperature. This unexpected result suggests that heating and cooling systems are in reality being used to suit the indoor temperature to the variable requirements of building occupants.

It is important to stress that there is evidence that acclimatised populations in their own homes find a wide range of temperatures, between 10 and 35 °C [17] are acceptable, to occupy during their habitual diurnal, or annual, lifestyle pathways through the familiar thermal landscapes of the spaces and places.

Figure 3.8 shows that acceptable temperatures in homes and offices vary not only by day and year but by month as well. These broad limits for acceptable comfort are demonstrated for adapted populations, who have to hand a functional range of adaptive opportunities that enable them to adapt themselves and their environments to achieve the goal of creating adequately comfortable conditions.

The control of air movement and clothing will influence the indoor environment which is found comfortable by the occupants. So where possible occupants should also feel free to adjust clothing, move to more comfortable places etc. This implies that it is not just the physical environment which is important but also the culture of the local population.

These considerations will also vary according to the purpose of the building so that a dwelling will be used differently than a workplace, and the level of operable adaptive opportunity may vary enormously, not only between buildings, but also between the mind-sets and cultural constraints of building owners, operators, managers, personalities and occupants (so management need to be aware of the 'cost' of a 'dress code').The financial responsibility for energy use can also change behaviours, driven by the desire to reduce or increase reliance on passive conditioning of buildings, as can the growing awareness of the environmental impacts of energy use in a heating world. Both of these factors influence the current move back towards designing buildings that can rely for as much of the day or year as possible using natural ventilation, and only relying on heating and cooling to condition buildings when needed.

3.5 Humidity and Comfort

There is a popular conception that humidity plays an important role in the thermal comfort of people. If humidity is measured as relative humidity (RH) it can appear important but that is because RH includes temperature in its definition, and this is reflected in the statistics. If instead of RH, the water vapour pressure is used to measure the effect of humidity the it is found to be small (Humphreys et al. [12], pp. 179–180). At the temperatures we are assuming within a warm building (say 30 °C) a difference in water vapour pressure from 0 kPa (zero humidity) to 4 kPa (about the maximum for air at this temperature) the difference in PMV is about 1. In reality the inside of an occupied room is unlikely to have anything like this range of humidity.

3.6 Conclusions

Ventilation is a key element of how people use, and appreciate, buildings. It is not just a matter of having enough air of the right quality, speed and temperature, but the air which moves through a building is an essential part of the deep and unspoken relationship between the building, its thermal landscapes and its occupants. The theory of thermal comfort allows for the estimation of the effect of moving air, and the ways in which its heat transfer properties are used by building occupants to make their dwellings, workplaces and lifestyles comfortable enough within the cultural and economic constraints of their own cultures, and personal circumstances.

Acknowledgments The author is indebted to Prof. Susan Roaf for suggestions and help with this chapter.

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Chapter 4
Ventilative Cooling in Standards, Legislation and Compliance Tools

Christoffer Plesner and Michal Pomianowski

Abstract The use of VC is strongly related to standards, regulations and national compliance tools. The chapter describes the current status and future recommendations for better implementation of ventilative cooling in standards, legislation and compliance tools. The content of the chapter is based on the extensive review of EN standards, ISO standards and national standards, as well as national legislation and national compliance tools. Information is also obtained through questionnaires answered by experts from 11 countries, all of which participated in the IEA EBC Annex 62. Study reveals that ventilative cooling is not well-integrated in standards, legislation and compliance tools. It also reveals that there is a broad field of evaluation methods for ventilative cooling, ranging from very simple to detailed, which can support a better integration of ventilative cooling in the near future.First in this chapter is presented status in: standards, legislation and compliance tools. Respectively the status is followed with recommendation on each.Chapter finishes with conclusions.

4.1 Preface

Ventilative cooling is an airborne system utilizing air from outside at its actual temperature and humidity that can be based on natural, mechanical or hybrid ventilation strategies making it possible to save cooling energy and give more flexibility and design options for buildings, enabling a broader range of design solutions to fulfil building energy legislations. The strategies are called natural, mechanical or hybrid ventilative cooling and will hopefully be used as terms in future technical documents, e.g. standards. But for ventilative cooling to become a more widely used solution,

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it needs to be well integrated into standards, legislation and compliance tools. This chapter will evaluate if this is the case or not.

4.1.1 Objectives of the Chapter

The overall objective of this chapter is to describe the current status and future recommendations for better implementation of ventilative cooling in standards, legislation and compliance tools. The content of the chapter is based on the extensive review of EN standards, ISO standards and national standards, as well as national legislation and national compliance tools. Information is obtained through questionnaires answered by experts from 11 countries, all of which participated in the IEA EBC Annex 62 (ventilative cooling), where IEA is the International Energy Agency, and EBC is the Energy in Buildings and Communities Programme. Detailed information on the evaluation of missing parameters in standards, legislation and compliance tools regarding ventilative cooling is available in the completed questionnaires of Annex A to C of the Venticool background report (can be found free online) [1].

4.1.2 Main Outcome

The conducted study from IEA EBC Annex 62 reveals that ventilative cooling is not well-integrated into standards, legislation and compliance tools. However, it also reveals that there is a broad field of evaluation methods for ventilative cooling, ranging from very simple to detailed, which can support a better integration of ventilative cooling in the near future.

Even though the benefits of ventilative cooling are widely acknowledged, its use by e.g. designers or architects strongly depends on a few intertwined challenges:

- The adequate modeling of natural ventilation and especially of airflow rates
- The share of the energy use for cooling for summer comfort and to avoid overheating risks, is close to becoming equivalent to the energy consumption for heating in winter, depending on the climate
- The adequate prediction of the expected "thermal comfort and cooling requirements", as well as the "energy performance" when using ventilative cooling in buildings (this could e.g. be based on static models (e.g. Fanger PMV model - Predicted Mean Vote) or adaptive models (e.g. adaptive comfort model)).

Although the first challenge can be handled by the use of adequate airflow models, the second challenge requires national ambitions and targets to be set up in building legislation and standards. Finally, the third challenge requires that both static and adaptive comfort models are supported in standards, building legislation and compliance tools.

The split of roles and responsibilities between standards, legislation and compliance tools differ from country to country. The collective task is to set up targets for certain parameters and methods to evaluate if these targets have been met. The targets are assumed to be defined in the legislation, and the methods to evaluate if the targets are met are defined in standards and/or national compliance tools.

4.2 Status of Ventilative Cooling

This section evaluates how ventilative cooling is treated in EN, ISO and national standards, as well as other technical documents e.g. Technical reports. Furthermore, national legislation and national compliance tools are evaluated by looking to which extent certain ventilative cooling parameters are integrated (e.g. cross ventilation or which calculation time step is used). One of the areas of interest are e.g. how to predict the expected "thermal comfort and cooling requirements", as well as the "energy performance" when using ventilative cooling in buildings. These may be predicted by using the so called "indicators", which may be based on either static models (e.g. Fanger PMV model) or adaptive models (e.g. adaptive comfort model).

For more detailed evaluation of missing parameters in standards, legislation and compliance tools for ventilative cooling, see the filled in questionnaires in Annex A to C in the Venticool background report [1].

4.2.1 Status in Standards and Other Technical Documents

There are many types of standards (EN standards, ISO and national standards) in relation to ventilative cooling. Furthermore, other technical documents exist such as Technical reports, which are often more descriptive than typical standards (often describing the content of a standard or a topic). Technical Reports are chosen to be part of this investigation as for example in the EPBD (Energy and Building Directive) package where there is one corresponding Technical Report per standard, e.g. CEN/TR 16798-8:2017 (Technical Report) related to EN 16798-7:2017 (EN Standard). A Technical Report has a lower status than an EN standard (two steps lower).

Some examples of relevant EN and ISO standards follow and could be split into different types, namely "system design" and "performance standards". System design standards deal with how to design the ventilation system in regard to ventilative cooling, and performance standards have to do with either the calculations or the requirements. In this section, this division of "system design" versus "performance" is only used for EN standards to easier distinguish EN standards' main contents from one another - this division would e.g. not make sense for the status in national legislation.

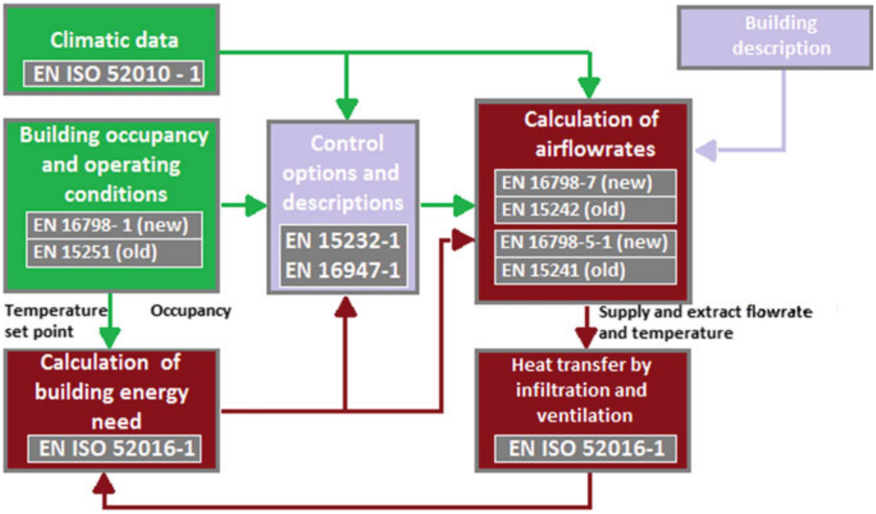

Fig. 4.1 Overview of EPBD standards relevant to Ventilative cooling, inspired by CEN/TR 16798-10 (PE draft, 2015) and updated to the current status of standards

Figure 4.1 provides an overview of the EPBD standards relevant to ventilative cooling [2], and their significant differences in terms of content, for example, EN 16798-1:2019 deals with building occupancy and operating conditions e.g. including the adaptive comfort model used by natural ventilation/natural ventilative cooling (in buildings without mechanical cooling). Figure 4.1 is inspired by the Figure from CEN/TR 16798-10 (PE draft, 2015) and is updated to the current status of standards it refers to.

Within CEN standards (before the revision of the EPBD package standards), relevant to ventilative cooling, and used in energy performance legislations (EN 15242:2007, EN 15241, EN 15251:2007 and EN 13779:2007) remain some critical limitations (e.g. control of systems; see next section for more detail). The aforementioned standards have been updated since then (see new numbers in following section) - though the conclusions remain the same. For example, how to properly reflect the effective cooling potential of outdoor air when applying seasonal or monthly methods, if both cooling demand and cooling potential vary on hourly basis.

The IEE CENSE project (2007–2010) includes summaries of Energy Performance of Buildings Directive (EPBD) related EN standards, though concluding on the previous version of the standards, but the main conclusions are very similar to the updated standards []. For updated information on the set of EPBD standards see the EPB Center - a service center for information and technical support:the internationally harmonized and coherent set of energy performance of buildings (EPB) assessment methods [site: https://epb.center/].

4.2.1.1 European Standards (EN) and Other Technical Documents (Status)

In this section, the status of relevant EN standards concerning ventilative cooling is evaluated.

Many EN standards relating to the 2010 recast of the Energy Performance of Buildings Directive (EPBD) have been revised up until 2017. Since then some of the standards have been under revision again. In this section, some of the important standards for ventilative cooling have been chosen for further elaboration; both new and old versions of the standards have been investigated in order to better understand the changes in the new revised versions. Some of the identified European standards are:

- EN 13779:2007 (now EN 16798-3:2017)
- EN 15251:2007 (now EN 16798-1:2019)
- EN 15242:2007 (now EN 16798-7:2017)

As briefly explained in the start of this section, standards could be split into different types, namely “system design” and “performance” standards.

System Design (how to design ventilation systems and what to consider when designing):

- System design standards e.g. CEN/TR 14788:2006 (under revision), EN 16798-3:2017 (under revision) and CEN/TR 16798-4:2017 (under revision))

Performance (performance aspects, e.g. calculation and requirement standards):

- Performance calculation (e.g. airflow rate calculations, e.g. EN 16798-7:2017 and CEN/TR 16798-10)
- Performance requirements (e.g. thermal comfort requirements, e.g. EN 16798-1:2019 and EN 15665:2009 (under revision).

In respect to European standards, there is a Technical Report, CEN/TR 14788:2006 (under revision) which covers some of the aspects of natural ventilative cooling by mentioning stack effect and cross ventilation. This Technical Report informs readers on what to be aware of when designing a natural ventilation system. Unfortunately, CEN/TR 14788:2006 (under revision) is not an EN standard, but “only” a Technical Report, which is two steps below an EN standard in status. Currently CEN/TR 14788:2006 together with EN 15665:2009 are under revision, so the above information explains only the current content. The new standard underway in CEN/TC 156/WG2 combining these 2 technical documents has the working title “Ventilation in buildings - Ventilation systems in residential buildings - Design” (prEN 15665:2020).

Overall there are European Technical Reports (TR’s) which to some extend cover some of the “system design” aspects of natural ventilative cooling in a building, such as CEN/TR 16798-4:2017 (TR to EN 16798-3:2017) and CEN/TR 14788:2006, but European EN standards covering this sufficiently are missing. As previously mentioned, technical documents CEN/TR 14788:2006, EN 16798-3:2017 and CEN/TR 16798-4:2017 are all under revision.

With the revisions of EN 15251:2007 (now EN 16798-1:2019) and EN 15242:2007 (now EN 16798-7:2017) some aspects of natural ventilative cooling are covered. However, other aspects are still missing or lacking in content in different areas (e.g. as identified by venticool [4]). Some of these missing parameters in the existing standards are:

- Control of systems
- Internal partition of buildings
- Guidance on parameters that shall be defined by the user or taken by default.

For more detailed evaluation of missing parameters in EN standards for ventilative cooling, see the filled in questionnaires in Annex A to C of the Venticool background report [1].

4.2.1.2 ISO Standards (Status)

There are many ISO standards which take ventilation into account, but only few ISO standards evaluate the effect of natural ventilative cooling on reducing cooling energy consumption or improving indoor thermal comfort. For example, ISO 13153:2012 shows a framework of a design process for energy-saving in single-family residential buildings and small commercial buildings. The "Energy consumption ratio" is determined in the standard by the location of the building and the method(s) for taking cross ventilation into account. ISO 7730:2005 also describes the effect of air velocity which is relevant to indoor thermal comfort, but this standard is intended for steady-state rooms.

ISO 18523-1:2016 specifies the formats to present schedule and condition of a building, zone and space usage, which is to be referred to as input data of energy calculations for non-residential buildings.

The schedule and condition include schedules of occupancy, operation of technical building systems, ventilation airflow rate, hot water usage and internal heat gains due to occupancy, lighting and equipment. ISO 18523-2 includes the same type of content but for residential buildings.

ISO 17772-1:2017 specifies requirements for indoor environmental parameters for thermal environment, indoor air quality, lighting and acoustics and specifies how to establish these parameters for building system design and energy performance calculations. It includes design criteria for the local thermal discomfort factors, draught, radiant temperature asymmetry, vertical air temperature differences and floor surface temperature.

For more detailed evaluation of missing parameters in ISO standards for ventilative cooling, see the filled in questionnaires in Annex A to C of the Venticool background report [1].

4.2.1.3 National Standards (Status)

In this section, the status of relevant national standards concerning ventilative cooling is summarised and shortly described for Japan and Australia to not only mention European national standards. The information presented here is based on the information collected through questionnaires that can be found in Annex A to C of the Venticool background report [1]. The report covers different climates with information for other countries as well, for example, Denmark, Switzerland and Australia, providing a broad overview of how ventilative cooling is implemented in national standards.

The Japanese national standard, “Energy saving standard for residential buildings, 2015” takes into account the effect of cross ventilation as a method for reducing the energy consumption for cooling. The level of air-change rate (ACH) options; (“none”, “5 ACH and more”, and “20 ACH and more”) is determined by the location of the building and the position of the openings (e.g. windows and internal doors). The effect of natural ventilative cooling has not yet been evaluated in the energy saving standard for non-residential buildings.

Australian Standards 1668.2 and 1668.4 namely: “The use of ventilation and air-conditioning in buildings. Part 2: Mechanical ventilation in buildings and Part 4: Natural ventilation of building” cover the requirements for mechanical and natural ventilation in occupied spaces. The objective of these two standards is to define the minimum ventilation rates per person or minimum window openings required for natural ventilation. They do not specifically address the design of ventilative cooling systems, nor the effect of using ventilation for cooling purposes. Only Australian standard 1668.2 suggests that when a mechanical HVAC system is in place an economizer damper should be installed.

4.2.2 Status in Legislation

In this section the overall status and overview of legislation concerning ventilative cooling is looked at. Legislation could be divided into national and regional legislation. The type of legislation differs from country to country, as not all countries have regional legislations. Furthermore, the way ventilative cooling is treated in legislation is evaluated by looking into what extent certain ventilative cooling parameters are integrated nationally (e.g. cross ventilation or which calculation time step is used).

The status of relevant national legislation concerning ventilative cooling follows, based on results from previously published reports (e.g. looking at the national building codes through questionnaires). Regarding legislation, a broad field of evaluation methods for ventilative cooling, ranging from very simple to detailed exists. For quite a few countries, among the reviewed ones, there is a lack of ventilative cooling integration in legislation and compliance tools e.g. in the United Kingdom, Italy and Japan. Generally, the calculation of air flow rates in buildings is not sufficiently reflecting the real conditions, being either the actual building design, physics or geometry, and thus undermining the full potential of ventilative cooling. For example, in Japan there is no legislation integrating ventilative cooling, but there will be an obligation to take an "energy saving standard" for residential buildings into account by 2020. The "Energy saving standard for residential buildings, 2015" takes the effect of cross ventilation into account. Further, Swiss legislation provides a sufficient framework to consider ventilative cooling by referring to Swiss norm, SIA 180 for thermal protection by taking into account the resulting air conditioning energy consumption for the energy label.

To understand the content given by the detailed evaluations from the Venticool background report it was chosen to include the Austrian reply (included below), to give insight into how Ventilative cooling is integrated in Austrian legislation.

4.2.2.1 Austrian Reply to Ventilative Cooling Implementation in National Legislation (an Excerpt from the Venticool Background Report) [1]

Question: Since when is the current national building legislation enforced?
Reply: March 2015.

Answer: When is the next revision of your national building legislation?
Reply: Presumably 2019.

Question: How is the air flow rate determined for ventilative cooling in your national building legislation/guideline?

Reply: Fixed air change rate (ACR) without any sensitivity to building design in case of cooling demand compliance tool. More detailed calculation incl. window position, size and temperature in case of IEQ compliance tool for free running rooms.

Question: Which standards/guidelines are referred to in your national building legislation/guideline (if relevant incl. short scope)?

Reply: For energy demand compliance, the calculation method is defined within ÖNORM B 8110-5, -6, ÖNORM H 5055, 5056, 5057, 5058 and 5059. All together they are Austria's answer to the EPBD requirements and Austria's Interpretation of EN ISO 13790. Within these standards, it is ÖNORM B 8110-5 which defines the outdoor climate and the usage input parameters. For summer comfort of rooms without cooling demand (obligatory for residential) buildings, compliance calculation is defined in ÖNORM B 8110-3. Its algorithms are closely linked to ISO 13791 and ISO 13792.

Question: Are the effects of actual window position and geometry of the building included in your national building legislation/guideline? (e.g. orientation and height difference between windows in building?).

Reply: Within the compliance tool for summer comfort, the ACH is calculated with a simplified formula from window area, window height and temperature difference. Windows in two different levels are accounted for. No option is given to take into account cross ventilation. No wind effect may be taken into account. The formula is:

$$\dot{V} = 0.7 \cdot C_{ref} \cdot A \cdot \sqrt{H} \cdot \sqrt{\Delta T} \tag{4.1}$$

where:

C_{ref} is the exchange coefficient, i.e. $C_{ref} = 100\ m^{0.5}/(hK^{0.5})$. If windows in two heights are applied, the surface calculation is altered to

$$A_{eff} = \sqrt{\frac{1}{\frac{1}{A_{oben}^2} + \frac{1}{A_{unten}^2}}} \tag{4.2}$$

Question: State the name of your national legislation/guideline and furthermore, indicate which parameters regarding ventilative cooling are included.

Reply: See filled in Table 4.1.

For more detailed evaluation of missing parameters in legislation for ventilative cooling, see the filled in questionnaires in Annex A to C of the Venticool background report [1].

4.2.3 Status in Compliance Tools

This section looks into the overall status and overview of compliance tools concerning ventilative cooling. The degree of complexity among national compliance tools can vary a lot and it is sometimes difficult to distinguish between national regulation and national compliance tools. The way ventilative cooling is considered in compliance tools is assessed by checking to what extent certain ventilative cooling parameters are integrated nationally (e.g. if cross ventilation or which calculation time step is used).

As regards compliance tools, a broad field of methods for ventilative cooling appears to be integrated, ranging from very simple to detailed. Actually, for quite a few countries there was a lack of ventilative cooling integration e.g. in the United Kingdom, Italy and Japan. For example, in Italy, upper limits on indoor temperature (i.e. according to the adaptive thermal comfort model) and thermal comfort/overheating indicators are not included in the energy performance evaluation; this could be improved. Switzerland's, Norway's and Austria's legislation appear to better integrate ventilative cooling through hourly time step calculations which better support the adaptive comfort model, instead of the less precise, monthly calculations. Another example is Denmark, which have started to improve the possibility of using ventilative cooling by making a distinction between single-sided and cross ventilation strategy. The selection is not possible directly through the software interface, but recommended airflow rates take these strategies into account recommending higher airflows for cross-ventilation than for single-sided ventilation. Also,

Table 4.1 Ventilative cooling parameters in your national legislation and or/guideline for residential buildings

Parameters	National standard ON B 8110-3 being obligatory referred to in national building code OIB RL 6 forming the compliance for summer comfort in buildings without cooling demand	National standard family ON B 8110-3, -6 and ON H 5055, 5056, 5057, 5058, 5059 being obligatory referred to in national building code OIB RL 6 forming the compliance for energy demand for heating, cooling and lighting in buildings
Single-sided ventilation	Yes	No, fixed ACH
Cross ventilation	No	No, fixed ACH
Stack ventilation	Yes	No, fixed ACH
Night cooling	Yes	Yes, at fixed ACH of 1,5 h^{-1}
Free cooling	Not applicable, since only meant for buildings without cooling demand	Now cooling demand in residential buildings is allowed. Result of cooling demand calculation has to be zero
Hybrid systems	Not applicable, see above	See above
Position of windows in building	Yes, partly: only regarding relative vertical distance of windows, not orientation	Not applicable, since ACH is fixed
Is wind included in your calculation?	No	Only by influencing the infiltration rate
Effect of having manual or automatic window operation	No	No
Steady-state or dynamic calculation?	Dynamic, on basis of a repeated design-day	Steady state, with some performance indicators having been derived from preliminary dynamic simulation
Time-step (monthly or hourly)?	Hourly	Monthly
Indicate important issue not included in this table		

simple relations between airflow rate and openable window area are included in the help file of the tool (not in the interface). This is on the right track, even though air flow rates should reflect the real conditions to a higher degree, based on actual building physics and geometry and allowing for more flexibility e.g. higher air change rates allowed in unoccupied rooms during night and lower if the rooms are occupied.

For more detailed evaluation of missing parameters in compliance tools for ventilative cooling, see the filled in questionnaires in Annex A to C of the Venticool background report [1].

4.3 Recommendations for Standards, Legislation and Compliance Tools - for Better Implementation of Ventilative Cooling

4.3.1 General

This section provides recommendations for better implementation of ventilative cooling into standards, legislation and compliance tools, based on the findings from section 4.2. In regard to legislation it is not always easy to align recommendations, due to the different ways ventilative cooling is included (or not) nationally and the differences in the use of calculation methods. Furthermore, this section discusses if new technical documents on ventilative cooling are needed, based on the findings.

All the recommendations that follow may be used as input to regulators on how to improve the implementation of ventilative cooling in future standards, legislation and compliance tools.

Overall a lot of recommendations were developed for standards, legislation and compliance tools which vary depending on the type of document and country. To conclude on all these recommendations, it was chosen to make specific overall recommendations given per topic (e.g. air flow rate) as proposed changes in standards, legislation and compliance tools, to be used directly by the target groups (building designers, builders and experts working with building energy performance standards, legislations and compliance tools) for future revisions of these documents. This section summarises the “overall recommendations across all standards, legislation and compliance tools”. For more specific details on recommendations on national level please see the recommendation sections on “national legislation” and “national compliance tools” in the Venticool background report [1]. The split-up of roles and responsibilities between legislation, standards and compliance tools differ from country to country. The collective task is to set up targets for certain parameters and methods to evaluate if these targets have been met. In the following paragraphs, the targets are assumed to be defined in the legislation and the methods to evaluate if the targets are met are defined in standards and/or national compliance tools.

4.3.2 Overall Recommendations in Standards and Other Technical Documents

The recommendations for EN standards are given below; first for EN standards and other technical documents, followed by ISO standards. Finally, the main recommendations are given across all standards.

4.3.2.1 European Standards (EN) and Other Technical Documents (Recommendations)

Evaluation of possible new technical documents on ventilative cooling in CEN.

To sum up, there was an overall lack of ventilative cooling integration, found in existing and revised European standards regarding "system design" and "performance" aspects of ventilative cooling, and therefore pre work items (PWI's) relevant to ventilative cooling applications were proposed to the European Committee for Standardization (CEN). These pre work items were approved and started up under CEN/TC 156 in various working groups in 2018. These CEN projects have the scope of making technical documents focusing on setting criteria and giving guidance to design of both ventilation systems (natural, mechanical and hybrid) and ventilative cooling systems (natural, mechanical and hybrid). These documents should guide the designers to what to be aware of when designing these systems and will further propose two main design approches, namely the "prescriptive approach" and the "performance-based approach". There is good development in these projects, with a plan to coordinate to eliminate overlaps.

The following 3 projects relevant to ventilative cooling applications have started up in 2018 in CEN:

- "Ventilative cooling systems"
  - Main focus: thermal comfort (reduce cooling loads and prevent overheating)
  - Document type: A CEN Technical specification
  - Work started up in WG/21 in CEN/TC 156.
- "Natural and Hybrid ventilation systems in non-residential buildings"
  - Main focus: indoor air quality
  - Document type: A CEN Technical specification
  - Work started up in WG/20 in CEN/TC 156.
- "Ventilation for buildings - Ventilation systems in residential buildings - Design (prEN 15665:2020)
  - Main focus: indoor air quality
  - Document type: Goal is to merge EN 15665:2009 and CEN/TR 14788:2006 into one document (EN standard)
  - One of the aims is to include the "performance-based design approach" and to expand the sections on design of Natural and Hybrid ventilation systems
  - Work started up in WG/2 in CEN/TC 156.

The initiated projects are foreseen to be released as European Technical Specifications (normative documents of lower status than EN Standards) and as an EN standard under CEN/TC 156. The technical documents are a good opportunity to define the design aspects of ventilative cooling and natural and hybrid ventilation systems on the European and International scene e.g. by applying findings from the venticool platform [5] and the final deliverables of the IEA EBC Annex 62 reports [6].

Some more concrete recommendations to the future implementation of ventilative cooling in EN standards follow:

- The initiated projects in CEN could contain separate sections on thermal summer comfort which is very relevant to ventilative cooling, explaining how ventilative cooling may reduce overheating (as in e.g. Japanese design guideline for ventilative cooling [7], CIBSE AM 10:2005 (first part of the guide (design) or in section "control of summer overheating") - currently under revision [8] and/or DS 447:2013 - currently under revision [9]);
- The initiated projects in CEN could give guidance on how to design ventilative cooling and natural and hybrid ventilation systems in buildings by giving a framework of design approaches and methods;
- In future standards "performance" aspects areas such as control of systems, internal partition of buildings and guidance on parameters that shall be defined by users, should be better integrated;
- In future standards it should be considered that windows are not the only mean to provide ventilative cooling but there are also other components already available on the market (i.e. louvre, operable opaque envelope parts, thermal chimneys, wind catchers, etc.) that can effectively contribute to overheating reduction;
- Building designers, builders and experts need more information on how to design, calculate and assess the performance of ventilative cooling systems, instead of only being given requirements to follow or general information on natural forces;
- Design of natural ventilative cooling systems should consider the effect of:
  - Height difference between windows or other opening types (e.g. stack effect from height difference betweeen facade and roof windows);
  - Placement of windows or other opening types in regard to noise, outdoor air pollution and security
  - Placement of windows or other opening types (opposite sides of building/room) in regard to maximum cross ventilation (advantage using this)
  - Control strategies
  - Window operation management according to outdoor climate and pollution conditions
  - Simple calculation methods for ventilative cooling.

The recommendations for ISO standards are given below, based on the findings from the filled in questionnaires, to be used directly by the target groups of this report for future revisions of these documents.

4.3.2.2 ISO Standards (Recommendations)

This section describes recommendations for better implementation of ventilative cooling in ISO standards. As in CEN, new work items relevant to ventilative cooling applications have been proposed to the International Organization for Standardization

(ISO) aiming at making a descriptive technical document focusing on the design process or aspects of natural ventilation systems.

The following project relevant to ventilative cooling applications have started up in ISO:

- "Design process of natural ventilation and hybrid systems for reducing cooling demand in non-residential buildings (NP 22511)"
  - Main focus: thermal comfort (design process to reduce cooling demands and/or overheating)
  - Document type: ISO standard
  - Work started up in WG/2 in ISO/TC 205.

The effect of cross ventilation on reducing cooling demand is described in ISO 13153:2012, but single-sided ventilation is excluded and buoyancy driven ventilation is not taken into account. This standard should be expanded to allow considering natural ventilation and hybrid systems. This standard describes the design process and thus the control strategy or methods for openable windows and cooling devices will be needed in other standards. No ISO standards for design methods of (large) non-residential buildings are available; hence, the new ISO standard, NP 22511 (in progress, explained above) is being developed under ISO/TC 205, WG2.

4.3.2.3 National Standards (Recommendations)

The recommendation is to base national standards on the same methods as in EN and/or ISO standards. See text below for further recommendations across all standards.

4.3.2.4 Overall Recommendations (Across All Standards)

The main recommendations across all investigated standards, summing up specific overall recommendations per topic (e.g. air flows) are presented below. To allow for ventilative cooling to be treated better in standards both at the design stage, where initial calculations of e.g. the natural forces are made as well as, at more detailed stages where more detailed calculations are needed, it is important that several parameters are taken into account, such as:

- Assessment of overheating, e.g.:
  - Utilizing thermal comfort indicators, including adaptive temperature sensation
  - Utilizing energy performance indicators
- Assessment of natural and mechanical ventilative cooling;
- Assessment of night cooling;

- Calculation methods that fairly treat natural ventilative cooling for determination of air flow rates including e.g. the dynamics of varying ventilation and the effects of location, area and control of openings.

When revising standards with respect to calculation and design of ventilative cooling systems ensure that the standards don't favour specific technologies and allow for emerging technologies such as hybrid systems and for components alternative to windows (i.e. louvers, thermal chimneys, wind catchers, …). Among other things, the determination of air flow rates in buildings for e.g. natural ventilative cooling is important to consider, where both simplified and detailed calculation methods can be found in e.g. calculation standard; EN 16798-7:2017, enabling the designer to choose which level of detail is needed for the given purpose and stage of the construction. It is recommended that the full effects of ventilative cooling are evaluated reflecting the real conditions for the building, control, use and climate. This should include in particular the actual building physics and geometry, supporting a fair evaluation of e.g. stack effects, cross ventilation, mechanical ventilation, control system, night/day ventilation and summer/winter ventilation.

Inspiration for recommendations in standards can be found in the published IEA EBC Annex 62 "Ventilative cooling design guide" [10], which gives information on how to design ventilative cooling systems by e.g. using Key performance indicators for "thermal comfort" and "energy performance" aspects. These key performance indicators are addressed in this section.

Air Flow Rate

Recommendation: Use main calculation standard, EN 16798-7:2017 for the calculation of air flow rates in buildings:

> We recommend using the standard, EN 16798-7:2017 for the calculation of air flow rates in buildings for ventilative cooling. The standard contains both simple direct methods and a detailed iterative method covering different needs and complexities. E.g. for quicker calculations, simple direct methods of calculation using wind velocity and temperature difference as input, can be used for single-sided and cross-ventilation, whereas for more detailed calculations, the detailed iterative mass-balance method calculation using internal reference pressure as input can be used.

Recommendation: Consider infiltration, natural and mechanical ventilation:

> A clear distinction between infiltration related air flow rates and natural ventilation airflow rates should be made. It must be clearly stated that infiltration airflow rate is the uncontrolled air flow while natural ventilation related air flow rate is controlled and may depend on several factors, such as, opening position, opening types, opening effective area, automation possibility, etc. If infiltration and natural ventilation airflow rates are not considered separately then high ventilation heat losses in the cold season would be observed since natural ventilation has no possibility for heat recovery and air flows should be significantly higher than for infiltration.

Recommendation: Flexibility allowing calculation of air flow rates based on real conditions:

When revising standards with respect to calculation and design of ventilative cooling systems ensure that both day and night ventilation are taken into account, for various scenarios, including window openings. Generally, we recommend that standards reflect the real conditions based on actual building physics and geometry. This increases flexibility to reach the relevant air flows depending on room type and thermal loads.

Air flow rates shall be adjustable depending on the ventilation need for: indoor air quality, overheating prevention, day/night and depending on season.

Thermal Comfort Indicators (e.g. Criteria for Overheating)

When revising standards with respect to the prediction of the expected thermal comfort and cooling requirements by using ventilative cooling, it is recommended to use a method that is based on the static Fanger model (PMV evaluation) (using mechanical ventilative cooling) or the adaptive comfort model (using natural ventilative cooling).

It is recommended to use Key Performance Indicators for "thermal comfort" that are used in the IEA EBC Annex 62 "Ventilative cooling design guide" (pp. 33–34) [10]. A set of two indicators enable to properly evaluate the thermal comfort; the Percentage outside the range (POR) (see method A, in CEN/TR 16798-2:2019) evaluating the percentage of occupied hours when PMV/operative temperature is outside the range and; according to the Degree hours criterion (DhC) (see method B, in CEN/TR 16798-2:2019), the time during which the actual operative temperature exceeds the specified range during the occupied hours is weighted by a factor which is a function depending on how many degrees the range has been exceeded.

Energy Performance Indicator (e.g. Criteria for Energy Performance)

It is recommended to use Key Performance Indicators for "energy performance" that are used in the IEA EBC Annex 62 "Ventilative cooling design guide" (see pp. 34–36) [10]: the cooling reduction requirement (CRR) evaluating the percentage of reduction of the cooling demand of a scenario, compared to a reference scenario and; the ventilative cooling seasonal energy efficiency ratio (SEER), which is defined as the cooling requirement saving divided by the electrical consumption of the ventilation system.

Alternatively, give a "penalty" associated to the energy performance of the building if cooling is needed - like the method used in the Danish compliance tool. This penalty raises awareness for the necessity of cooling and encourages the implementation of an efficient ventilative cooling system. In southern Europe cooling need will occur anyway during summer period, so a penalty could be given if the building has a cooling need in the shoulder seasons.

Flexibility Towards New/Alternative Technologies

When revising standards with respect to calculation and design of ventilative cooling systems ensure that new and alternative technologies are allowed. It is recommended that technologies such as hybrid ventilation are supported where the full effect of natural ventilative cooling used during periods of overheating is evaluated reflecting on the real conditions based on actual building physics and geometry.

4.3.3 Overall Recommendations in Legislation

The main recommendations are given below together with specific overall recommendations per topic (e.g. thermal comfort indicator) covering all investigated legislations. To allow for ventilative cooling to be treated in building performance evaluations, several parameters are necessary to take into account, such as:

- Assessment of overheating, e.g.:
  - Requirements to thermal comfort, including adaptive temperature sensation
  - Requirements to energy performance including cooling
- Acknowledgement of natural and mechanical ventilative cooling;
- Support to evaluation methods considering the dynamics of varying ventilation and ventilation modes;
- Support to evaluation methods considering the effects of location, area and control of openings.

When revising legislation with respect to calculation and design of ventilative cooling systems, ensure that the legislation is technology neutral thereby not favouring specific technologies and allowing emerging technologies such as hybrid systems. It is recommended that the full effects of ventilative cooling are evaluated reflecting the real conditions for the building, control, use and climate. This should include in particular the actual building physics and geometry. Legislation should include or refer to guidelines, standards or compliance tools on how to calculate the cooling effect, resulting temperatures and the energy performance.

4.3.3.1 Overall Recommendations (Across All Legislations)

Below are specific overall recommendations given per topic as proposed changes across all legislations.

Thermal Comfort Indicator (e.g. Criteria for Overheating/Overcooling)

Methods for a long-term evaluation of thermal comfort conditions should be taken into consideration and used actively as a requirement in the national legislation as supported by EN 16798-1:2019 and the associated Technical report, CEN/TR 16798-2:2019. CEN/TR 16798-2:2019 proposes different long-term evaluation methods e.g. the "percentage outside the range index" (method A) and the "degree-hours criterion" (method B) enabling the evaluation of both frequency and severity of overheating occurrences. The reference comfort temperature and the evaluation of overheating and overcooling can be derived from the Fanger model or the adaptive comfort model.

Available Opening Area for Natural Ventilative Cooling

Since natural ventilative cooling is highly dynamic, the legislation should support evaluation methods based on the actual building geometry, climatic conditions and actual use and control of the building. Necessary opening areas should be based on calculations where discharge coefficients of openings have been included.

Criteria for Draught Risk

The legislation should require the use of draught rate calculation according to ISO 7730 by using one of the three categories (A, B or C) for the evaluation. Draught due to air inlets will be related to their position in the room and distance from the occupied area. A description should be given for the occupied zone which should fulfil the requirements. A deviation from the requirements could be suggested if the air velocity is under personal control e.g. by using openable windows, table- or ceiling fans. It should be noted, that under thermal summer comfort conditions with indoor operative temperatures above 25 °C, increased air velocity can be used to compensate for increased air temperatures if the increased air velocity is under personal control. The correction value depends on the air speed range of the appliance. Draught rate should include temperature, air velocity and turbulence intensity, meaning e.g. that with higher temperatures, higher air speed is accepted.

In order to avoid other types of discomfort (e.g. flying papers, ingress of leaves, slamming doors etc.) in the occupied zone, one may set upper limits for air velocities different from the pure thermal draught assessment.

All Day Ventilation

Legislation should require that ventilative cooling can be applied during both occupied and unoccupied periods, meaning all day if needed. For openings used for ventilation, legislation should require considerations on the need for burglary, noise, pollution, rain and mosquito proofing.

4.3.4 Overall Recommendations in Compliance Tools

The main recommendations across all investigated compliance tools, summing up specific overall recommendations per topic are presented below. It is essential that national compliance tools can interpret the legislation in a fair and correct manner in order for the increased use of ventilative cooling to become fully relevant in different countries.

4.3.4.1 Overall Recommendations (Across All Compliance Tools)

Natural ventilative cooling is difficult to assess in most of the existing national compliance tools, which should reflect what is stated in the national legislation. Since compliance tools are the only evaluation tools used in many cases, it is recommended to secure the implementation of ventilative cooling in compliance tools, allowing the evaluation of over-heating issues at the earliest stage of design process when decisions on e.g. windows location or orientation can still be taken. Compliance tools simplicity (e.g. by elevated level of user-friendliness) is aligned with tight design budgets resulting in the situation where often these tools are the only design tool especially in the early design stages. This observation highlights the necessity of implementing ventilative cooling in compliance tools to promote its use, but also to secure that it is considered at the earliest stage of design process when decisions on e.g. windows location or orientation can still be taken.

To allow for ventilative cooling to be treated in building performance evaluations, several parameters should be considered, such as:

- Assessment of overheating, e.g.:
  - Thermal comfort indicators, including adaptive temperature sensation
  - Energy performance indicators like e.g. virtual cooling needs, cooling consumptions etc.
- Assessment of increased air flows when efficient ventilative cooling systems are used:
  - Differentiation should be made i.e. for cross- or stack ventilation versus single-sided ventilation, automated systems vs. manually controlled, large versus small opening areas
  - Associated airflows should preferably be based on building physics for e.g. dynamic tools (using pressure equations) or - as a simpler solution - on "coefficients" which increase air flows based on the chosen system
- Implementation of different levels of approaches to the evaluation of ventilative cooling, depending on the level of detail needed for the given purpose and stage of construction:
  - Simplified approach:
    Using national compliance tools based on monthly calculations with specific assumptions on input air flows for natural ventilation and ventilative cooling (like e.g. in Belgium, Flanders). The main benefit of this method is its direct applicability towards most existing compliance tools.
    It allows modelling of ventilative cooling via the use of constant air flows over a given period, and can, like in Belgium, promote the gradual use of openable windows, stack effect, cross-ventilation and even control systems.
    Its simplicity will of course lower the air flows and tends to reduce the impact of ventilative cooling on thermal summer comfort.
  - Intermediary approach (combining simplified and detailed approach):
    Using national compliance tools based on monthly calculations + using an add-on tool or plugin to address thermal summer comfort and ventilative cooling in a more accurate way (like e.g. in Denmark).
    The main benefit of this approach is to keep the existing compliance tool, but could be less accurate (and then less beneficial to ventilative cooling) due to the reduced number of parameters (in several cases, this tool will usually be using the same input parameters as the main compliance tool).

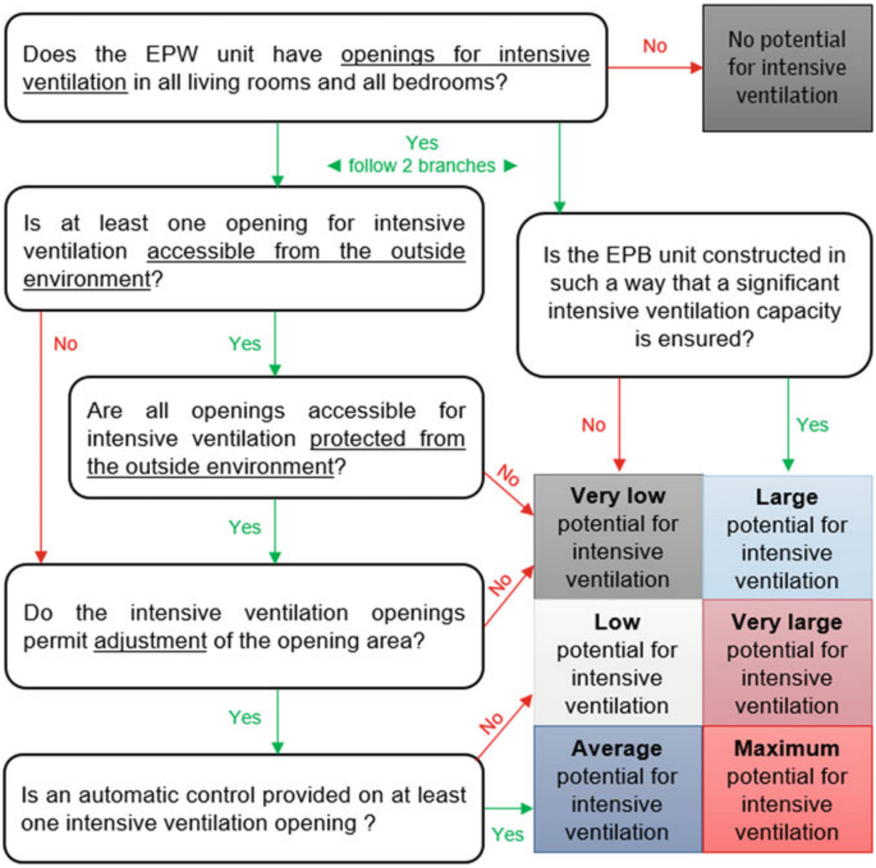

Fig. 4.2 Ventilative cooling potential (assessment flowchart)

– Detailed approach:
  Using national compliance tools based on full dynamic calculations (e.g. like in Switzerland, where several simulation tools from the market are allowed).
  Using national compliance tools based on simplified hourly calculations (like e.g. in France or in The Netherlands).

Examples on Different National Evaluation Approaches for Ventilative Cooling in Compliance Tools:

In most cases, simplified approaches underestimate the impact of ventilative cooling. Advanced calculation methods like e.g. dynamic simulations based on hourly time-steps are usually closer to reality and lead to more realistic air change rates. Examples of different "levels" of approaches to the evaluation of ventilative cooling in national legislation ranging from simplified to detailed, as explained in the above three bullet points, follow. The three following examples show interesting national approaches used for compliance tools. These methods are using different ways to evaluate air flows and thermal summer comfort, by making use of the technical possibilities of each tool (e.g. static tool, hourly tool, dynamic hourly tool…).

Belgium: Simplified Approach (To Provide Monthly Inputs).

Since January 2018, the Belgian region Flanders, has introduced a new evaluation method for ventilative cooling in residential buildings to be used in the EPB compliance tool. It consists of a simple chart flow for designers, which identifies the potential for ventilative cooling (ranked from "No potential" to "Maximum potential") [11]. This approach is simple and promotes the use of ventilative cooling, by ranking solutions based on their efficiency potential (e.g. accessible from the outside, protected from the outside, possible adjustment of opening area, automatic control). The impact of ventilative cooling is then assessed according to its effect on the thermal comfort indicator but could also be implemented to energy cooling needs (Fig. 4.2).

Denmark: Intermediary Approach (Add-on Tool to Improve the Evaluation of Thermal Summer Comfort).

Since 2015, the Danish Building Institute - SBi, has implemented an additional feature to the official compliance tool to evaluate thermal comfort. This module is called "Summer comfort" and is used to document the thermal comfort in summer in residential buildings through hourly calculations (described as total number of hours above 27 and 28 °C). Due to the limited number of parameters available in the main compliance tool, only some features of ventilative cooling can be considered in the add-on module, but it still allows the promotion of cross-ventilation, number of openable windows and geometrical free area of windows. Even though these compliance tools are limited for the modeling of ventilative cooling, the Danish approach shows that more advanced simulation tools can be developed and connected to the existing compliance tool, without jeopardizing well-known approaches.

Switzerland: Detailed Approach (Dynamic Simulation Software Allowed).

The Swiss regulation MuKEn shows a specific approach for the energy calculation, and allows the use of several simulation tools available on the market. This approach brings more flexibility regarding the use of ventilative cooling as most software are dynamic (hourly) simulation tools, which is the most accurate way of evaluating air flows (simplified methods usually tend to lower the impact of ventilative cooling in order to be conservative). Allowing several simulation tools could also lead to some disadvantages due to potential differences in input data if not standardized. Therefore, projects results might not be comparable with the results of other softwares. The use of software like e.g. DIAL + promotes a realistic effect of ventilative cooling and considers influent parameters like e.g. window dimensions, stack effect, cross-ventilation or automatic control.

The main recommendations from the IEA EBC Annex 62 (ventilative cooling) are given below together with specific overall recommendations per topic covering all investigated compliance tools; these are listed as proposed changes in compliance tools.

Airflow Rate

Recommendation: Air flow rates to be used for ventilative cooling should be either assessed or at least provided as input value.

- When technically possible, air flow or air flow rates should be evaluated based on building features and climatic conditions
- When incompatible with national compliance tool(s), simplified approaches should be provided to building designers by e.g. providing fixed average air flow rates to be used for "cooling" purposes
- When provided as input value, air flow rates should be divided into several levels to account for various systems efficiency (cross- or stack ventilation vs. of single-sided ventilation, automated systems vs. of manual control, large vs. of small opening areas)
- When air flow rates are accounted for via fixed values in compliance tools, the user must be able to specify different input values depending on the considered season (e.g. one value for winter, one value for summer). This is the only way to avoid a negative interaction between the heating and the cooling season, and to avoid that air flow rates associated with ventilative cooling are used all year long
- Air flow rates shall be adjustable depending on the ventilation need and on occupied/not occupied time for indoor air quality or overheating prevention. *Recommendation*: consider infiltration, Natural and Mechanical ventilation.
- Clear distinction between infiltration related air flow rates and natural ventilation airflow rates should be made. It must be clearly stated that infiltration airflow rate is the uncontrolled air flow while natural ventilation related air flow rate is controlled and may depend on several factors, such as, opening position, opening effective area, automation possibility, outdoor conditions etc. If infiltration and natural ventilation airflow rates are not considered separately then high ventilation heat losses in the cold season would be observed since natural ventilation has no possibility for heat recovery and air flows should be in general significantly higher than for infiltration.

Available Opening Area.

- The compliance tool should - as an additional feature - be able to estimate air flow rates from a given list of predefined openings (inlets and outlets), for example "window top hinged", "window side hinged" and "louvre" when they are fully opened, allowing for the possibility to overwrite this feature. In addition, it should introduce some interpolation of some intermediate openings. Discharge coefficients should be included in the predefined units. Based on this, the tool should confirm if the designed opening areas provide sufficient air flow rates.

Criteria for Draught Risk.

- In modern airtight buildings, draught due to infiltration is almost non-existing in cold climates and reduced in warmer climates. Then draught is therefore mostly related to deliberately made inlets. Simple compliance tools are hardly designed or suitable for draught calculations and separate tools for evaluations are often necessary.

Flexibility Towards New/Alternative Technologies.

- Compliance tools should be updated regularly with respect to calculation of the new ventilative cooling technologies, such as diffuse ceiling ventilation for natural and mechanical ventilation, ventilation units accounting for heat/cold storage and utilization of phase change materials (PCMs), hybrid ventilation systems and others. Moreover, more effort should be made to integrate components promoting ventilative cooling in compliance tools, like wind chimneys, air vents, trickle vents, and many others. At present, these components are poorly or even not at all included in compliance calculation tools.

4.4 Conclusion

The study reveals that ventilative cooling is in most cases not sufficiently integrated into standards, legislation and compliance tools. However, it also reveals that there is a broad field of evaluation methods for ventilative cooling, ranging from very simple to detailed that can support a stronger integration of ventilative cooling in the near future. Even though the benefits of ventilative cooling are widely acknowledged, its use by e.g. designers or architects strongly depends on a few intertwined challenges:

- The adequate modelling of natural ventilation and especially of air flows
- The share of the energy used for cooling to provide summer comfort and avoid the overheating risk tends to become equivalent to the energy consumption for heating in winter, depending on the climate
- The adequate prediction of the expected "thermal comfort and cooling requirements", as well as the "energy performance" when using ventilative cooling in buildings (this could e.g. be based on Static models (e.g. Fanger PMV model) using mechanical ventilative cooling or on Adaptive models (e.g. adaptive comfort model)) using natural ventilative cooling.

For an easier overview, the conclusions are split up into standards, legislation and compliance tools as seen below.

Standards and Other Technical Documents

There was generally a lack of ventilative cooling integration, in most of the evaluated countries e.g. United Kingdom, Belgium and China. In Japan, there is no legislation concerning ventilative cooling, but there will be an obligation to take into account an "energy saving standard" for residential buildings by 2020. The "Energy saving standard for residential buildings, 2015" takes into account the effect of cross ventilation.

Calculation of airflow rates in buildings should reflect the real conditions based on actual building physics and geometry. This allows for flexibility e.g. higher air change rates allowed in unoccupied rooms during night and lower when occupied. In conclusion, there was generally a lack of ventilative cooling integration, in existing and revised European standards regarding "system design" and "performance" aspects of ventilative cooling, and therefore pre work items (PWI's) relevant to ventilative cooling applications were proposed to the European Committee for Standardization (CEN). These pre work items were approved and have now started up under CEN/TC 156 in various working groups since 2018, with the scope of making technical documents focusing on setting criteria and giving guidance to design of ventilation systems (natural, mechanical and hybrid) and ventilative cooling systems (natural, mechanical and hybrid).

To allow for ventilative cooling to be treated better in standards both at the design stage, where initial calculations of e.g. the natural forces are made as well as, at more detailed stages where more detailed calculations are needed, it is important that at least the following point is taken into account:

- The support of calculation methods that fairly treat natural ventilative cooling for the determination of air flow rates including e.g. the dynamics of varying ventilation and the effects of location, area and control of openings.

Finally it is also recommended to use the Key Performance Indicators used in the IEA EBC Annex 62 "Ventilative cooling design guide" for "Thermal comfort" (Percentage outside the range and the Degree-hours' criterion) and "Energy performance" (Cooling reduction requirement and the Ventilative cooling seasonal efficiency ratio).

Legislation

Several countries have taken significant steps to better implement ventilative cooling, especially countries like Switzerland, Norway and Austria which allow hourly time steps for thermal comfort evaluations. This important decision generally allows for better inclusion of highly dynamic measures such as ventilative cooling. Also, e.g. Denmark has implemented an add-on module which supports the hourly approach for over-heating evaluation. This happens in a simplified module outside the monthly energy performance evaluation tool used in Denmark. This approach could potentially allow for a reasonable evaluation of the over-heating risk but is more difficult to be used in the energy performance evaluation. Furthermore, in Switzerland, legislation provides a sufficient framework to consider ventilative cooling by referring to norm; SIA 180 for thermal protection which takes into account the resulting air conditioning energy consumption for the energy label.

To allow for ventilative cooling to be treated better in building performance evaluations in legislation, several parameters are necessary to be taken into account in the building regulation; it is thus important that at least the following point is considered:

- Assessment of overheating, e.g.:
  - Requirements to thermal comfort, including adaptive temperature sensation
  - Requirements to energy performance including cooling.

Compliance Tools

Because of the dynamic nature of ventilative cooling, the recommendation is to implement hourly calculation time steps, instead of less precise monthly calculations, in more compliance tools for both thermal comfort and energy performance evaluations for a better support of adaptive comfort. The hourly calculations have the capability to predict the cooling loads in the building and hereby assess the overheating more precisely than the monthly calculations, which is crucial in many of the buildings nowadays. To allow for ventilative cooling to be treated better in compliance tools evaluations, it is important that at least the following points are taken into account.

Assessment of increased air flows when efficient ventilative cooling systems are used:

(a) Differentiation should be made i.e. for cross- or stack ventilation versus single-sided ventilation, automated systems versus manual control, large versus small opening areas
(b) Associated airflows should preferably be based on building physics for e.g. dynamic tools (using pressure equations) or - as a simpler solution—on "coefficients" which increase air flows based on the chosen system.

Lastly it is important to evaluate if the current methodology for the evaluation of ventilative cooling in compliance tools is sufficient to assess overheating. In contrast to most European countries'—where compliance tools using the monthly average models for energy calculations can underestimate the cooling potential of ventilative cooling - Denmark has been moving forward with the implementation of an additional feature to the official compliance tool to evaluate thermal comfort. The official compliance tool is based on monthly calculations, whereas the integrated module called "summer comfort" in the official compliance tool performs hourly calculations for thermal comfort in summer in residential buildings only. This method could be seen as an "intermediary" approach, in between the simplified monthly average models and the more dynamic hourly-based models. Although the "add-on" module method is a step forward, it is equally important that the calculated or allowed air change rates are high enough to actually achieve the needed cooling effect. Improvements in the "Danish" method are still needed - e.g. by ensuring the associated airflows are preferably based on building physics for e.g. dynamic tools (using pressure equations).

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Chapter 5
Ventilative Cooling and Air Pollutants

Guilherme Carrilho da Graça and Nuno R. Martins

Abstract The majority of office and other non-domestic buildings use mechanical cooling and ventilation, even when an optimized natural ventilation (NV) system could meet cooling and fresh air requirements. However, in most large cities, the outdoor environment is contaminated with a combination of noise, fine particles, heat and toxic gases. This contaminated environment has a detrimental impact on naturally ventilated buildings due to their lack of filtration and outdoor noise attenuation systems. This chapter presents a numerical analysis of the effect of fine particle pollution (PM2.5) on the NV potential of office buildings in California, Europe and Asia. Several years of measured weather and PM2.5 concentration data were used to perform dynamic thermal and airflow simulation analysis. Detailed simulation results show that a hybrid NV system can reduce the air-conditioning and ventilation electricity consumption of a well-designed office building by up to 83% (which can be increased to up to 93% by the availability of personal comfort systems), in comparison to an office using, during all working hours, a mechanical cooling and ventilation system equipped with a high-efficiency particle filter. Unfortunately, in this hybrid approach, high levels of outdoor PM2.5 penetrate the indoor environment, increasing occupant cumulative exposure by up to six times. To overcome this problem, two exposure control approaches were tested. Using NV only during moments of low outdoor PM2.5 concentrations limits the exposure increase to up to three times but at the cost of reducing energy savings. Equipping NV openings with an electrostatic filter would result in a similar exposure reduction, but at a very low energy cost, taking full advantage of NV's saving potential.

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5.1 Introduction

Over the last two centuries, human urban population has been continuously increasing. This shift, which started with the industrial revolution, gained momentum after the Second World War and resulted in the worldwide urban population exceeding rural population for the first time in 2007. By 2050, this continuously growing urban population is expected to be twice as large as the rural population, which has stagnated since the beginning of the twenty–first century [1]. This urbanization movement has increased the number of large cities and, in the more populated countries, the number of megacities (urban locations where tens of millions of people live and work [2]).

In urban environments, people increasingly spend most of their time indoors, whether at home, at work, at school or when taking part in other activities [3, 4]. This trend has contributed to increase use of building air conditioning (also known as mechanical heating, cooling and ventilation, or HVAC—Heating, Ventilation and Air Conditioning) and other electric equipment, which in turn has created a large energy demand. Recent concerns over the environmental consequences, such as air pollution and climate change, have set forth the pursuit of increased energy efficiency and, in the particular case of the building sector, low–energy thermal comfort solutions that limit the use of HVAC systems [5, 6].

One of these solutions is natural ventilation (NV), which occurs when pressure differences generated by wind or buoyancy forces act on one or more openings on the building envelope. Throughout history, NV has always remained the preferred choice for residential buildings [7, 8], while in commercial buildings, NV went from being the single option to somewhat of a lost art as mechanical ventilation (MV) systems became the standard during the second half of the twentieth century.

The hiatus in NV use in commercial buildings resulted in the loss of existing design know–how in a period were comfort and ventilation system performance standards have continuously risen. Fortunately, interest and use of NV in commercial buildings has been rising, especially during the last decades [9–12]. In the milder months of the year, NV can be an alternative to mechanical systems due to its potential to reduce ventilation and cooling related energy demand as well as sick building syndrome [13–15]. Unfortunately, the negative health effects of air pollution have recently gained notoriety and are already limiting the use of NV in urban areas [16].

In the last decades of the twentieth century, the health impacts of air pollution became well established in the realm of common knowledge [17, 18]. The term air pollution refers to a group of airborne pollutants that are known to contribute to decreased life expectancy [2]. These include pollutants that consist of one or two substances, such as carbon monoxide (CO), sulfur and nitrogen oxides (SO_x and NO_x) and ozone (O_3), as well as airborne particulate matter (PM), which includes several substances in a wide spectrum of particle sizes. Man-made pollution has resulted in the annual mean levels of airborne fine particles in the largest cities exceeding the World Health Organization's (WHO) guidelines for yearly and short–tem human exposure [19]. Although gravity forces the deposition of particles with diameters above 30 μm [20], smaller particles, in particular PM2.5, which are liquid or solid matter with an aerodynamic diameter below 2.5 μm that are suspended in the air, remain suspended for long times and can travel far from their sources.

The effects of human exposure to PM2.5 are especially felt in urban environments, where the higher population density gives rise to a higher pollutant generation combined with a higher density of human targets [2, 21]. For instance, dense city centers have a containment effect on black carbon emissions from fossil fuel–powered transportation, domestic stoves and space heating [22, 23]. The high pollution levels that are found in the environment of largest cities are transported into the indoor environment by the ventilation air. The most widespread approach to limit indoor PM2.5 levels in commercial buildings is the use of cloth filters integrated in MV systems. These filters can reach PM2.5 removal efficiencies above 90%, albeit at the cost of placing a large pressure load on the ventilation system and increasing the energy consumption of the ventilation fans to levels which are comparable to indoor lighting, with power densities in the range of 5 to 15 W/m^2 [24, 25]. Further, the average energy consumption of a mechanical cooling system has a similar magnitude (or up to twice as much in hot and humid climates), compounding an HVAC–related energy consumption of 50–60% of the total building energy consumption [26, 27]. In locations where electricity generation is based on fossil fuels, this higher power consumption further increases PM2.5 emissions into the environment. In contrast, NV with open windows does not increase PM2.5 emissions. However, NV airflow is driven by low pressure differences, which does not allow the use of cloth filters, enabling the unobstructed inflow of outdoor fine particles.

One approach to break this vicious cycle with limited occupant exposure consists in combining NV with a mechanical HVAC, in a hybrid system that can automatically alternate between the two indoor climate control approaches. When weather conditions are favorable, the use of NV leads to lower energy consumption. Unfortunately, in many cities, there are a significant number of hours when weather conditions are favorable to the use of NV but outdoor PM2.5 levels are high. To avoid contamination during these moments, an automated window control system would only allow for NV use when outdoor PM2.5 levels are below a safe threshold for long–term exposure. During moments with outdoor PM2.5 levels exceeding that threshold, the HVAC system would be in operation, conditioning the indoor environment and indoor PM2.5 levels. The energy savings that result from this hybrid cooling and ventilation system depend on local weather and outdoor PM2.5 levels as well as window–opening requirements. In the case of well–designed buildings with low internal gains, windows that are user–controlled were found to be opened for temperatures as low as 10 °C [28], while the typical maximum outdoor temperature for the use of NV in offices is approximately 26 °C [29]. When needed, both user–controlled and automated openings can be expected to be open within this outdoor temperature range. Thus, a potential for NV use can be quantified by the fraction of working hours when weather conditions are favorable for its use, that is, when the outdoor temperature is between 10 and 26 °C. A given building may use this full potential if there is a need for NV during all these hours, as long as the outdoor PM2.5 levels are not excessive. In warmer climates, an increasingly used approach to supplement natural cooling and ventilation systems consists of low–power consuming individual or localized heating and cooling devices, known as personal comfort systems (PCS) [30]. Localized cooling PCS can allow users to tolerate higher indoor temperatures (up to 30 °C, if humidity does not exceed 80% [31]), thereby increasing the maximum outdoor temperature that allows for NV use. These systems are usually based on air movement that increases the occupants' heat loss. PCS operating with this principle include chairs with fans [32], ceiling fans [31] or small fans that direct air flow to specific body parts, such as the face or torso [33]. Heating PCS, such as electrically heated chairs [34], typically consist of an electric resistance or radiative element [30], allowing occupants to tolerate a lower indoor temperature. In addition to increasing the NV potential, due to allowing its use with higher outdoor temperatures, PCS devices can also be used alongside conventional HVAC systems. In these cases, the benefit of these systems is to allow for higher cooling and lower heating set points.

Overall, the effect of the inter–relation between PM2.5 concentrations, weather and NV use on commercial building energy consumption and occupant exposure must be addressed. Answering this question requires a simultaneous energy and PM2.5 assessment of the trade–off between NV–induced energy savings and the resultant increase in indoor exposure to PM2.5 that arise from the use of NV.

The introduction section of this chapter presents a review of existing research on the impact of PM2.5 in the built environment [35]. Specifically, this review identifies the main sources and sinks of PM2.5 in indoor urban environments and the simulation tools that can be used to predict indoor PM2.5, as well as the most promising solutions to minimize building occupant exposure. Section 5.2 describes the analysis approach used in detailed simulation analysis of the impact of PM2.5 on the use of NV in commercial buildings. Section 5.3 presents the results of this analysis, followed by the conclusions.

5.1.1 Indoor Environment

In the modern urban environment, people spend most of their time indoors, whether at home, at work, at school or even when engaging in leisure activities [3, 4]. Thus, understanding the relation between the indoor and outdoor PM2.5 levels is the key to characterize exposure. The building envelope is an interface and a filter between indoor and outdoor environments and, in the absence of significant internal sources, indoor levels are expected to be lower than outdoors.

Particles in the outdoor environment are brought indoors by airflow, namely through a combination of infiltration, natural and mechanical ventilation. A small fraction of particles transported by the infiltration airflow through cracks and other unintended small openings do not fully transverse those openings, however nearly all sub–micrometer particles and above 70% of those between 1 and 2.5 μm in diameter do penetrate into the indoor environment [36]. In the case of MV, cloth filters can be used to limit the penetration of PM2.5. These filters can reach high PM2.5 retention rates, albeit at the cost of a very high pressure load, which increases the power–consumption from the ventilation fans. As for NV, airflow is driven by a low pressure difference, which does not allow for the use of cloth–based air filtration. As a result, in NV systems, outdoor PM2.5 is free to enter the indoor environment without obstruction.

PM2.5 can also be generated in the indoor environment. The combustion of coal [37–39], wood [40, 41] and other biomass fuel [42–45] for heating and cooking is an important source in residential buildings. Smoke can be emitted both directly into the home and indirectly, since smoke emitted to the outside can re–enter the building through the infiltration airflow [46]. Cooking also contributes to indoor PM2.5 emissions in homes, restaurants and cooking areas in other building typologies (offices, schools, etc.), since food preparation at high heat leads to the emission of water vapor and other solid and liquid particles [47–49]. Other combustion instances, such as the use of incense [50, 51], candles [47] and cigarettes [52], also emit PM2.5 into the indoor environment. Printers (and similar devices, such as fax machines or photocopiers) [47, 53] and chalkboards [41, 54] increase PM2.5 levels in schools and office spaces. Other indoor PM2.5 sources include anti–insect [55] and electric air freshener devices [52], as well as cleaning agents and cosmetics [52, 56], such as perfumes and hair sprays [47]. In addition to these sources, one of the most common contributors to high indoor PM2.5 levels in all buildings is the re–suspension of particles that have previously settled onto surfaces [57, 58]. This re–suspension is promoted by occupant movement and, therefore, is most relevant in indoor environments where movement is frequent, such as residential buildings and schools [47, 59–61]. Surprisingly, cleaning activities, such as sweeping, dusting or vacuum cleaning, can also contribute to re–suspend settled particles [47, 59].

The ratio between indoor and outdoor PM2.5 concentrations, known as I/O, is a simple indicator that provides a preliminary evaluation of the building's indoor PM2.5 pollution [3]. Figure 5.1 shows the range of measured I/O ratios according to building typology, ventilation strategy and strength of internal PM2.5 sources.

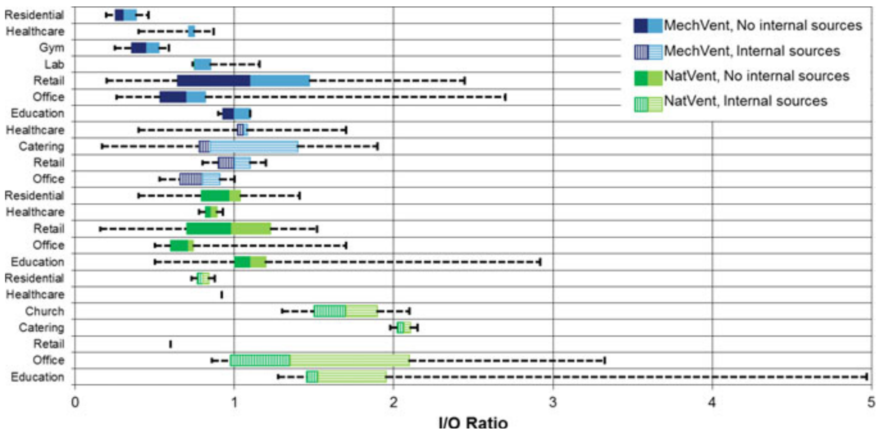

Fig. 5.1 Selection of studies with PM2.5 I/O ratios by building typology, ventilation type and existence of internal sources the box plot represents minimum, 25th percentile, median, 75th percentile and maximum

Table 5.1 Average PM2.5 I/O ratios by ventilation type and existence of internal sources

Ventilation	Indoor sources	Average I/O (%)		Standard deviation
Mechanical	No	0.77	100	0.36
	Yes	0.98	127	0.38
Natural	No	0.95	123	0.35
	Yes	1.81	234	0.95

In naturally ventilated buildings with low internal particle sources, the average I/O ratio is close to one, that is, indoor and outdoor PM2.5 concentrations are identical [48, 53, 62–72]. Also, as expected, without the influence of internal sources, the indoor concentration is dominated by the outdoor concentration, as indicated by the high correlations between both concentrations [62, 65–67, 73]. However, when significant indoor sources are present, the correlation is lower and the I/O ratio is nearly double, on average, than that ratio in buildings with no indoor sources [48, 59, 74–77]. The difference in I/O ratio was especially evident in studies that measured buildings with both low and high internal particle sources [47, 54, 75, 78].

Similarly, in mechanically ventilated buildings, the existence of internal sources [47, 53, 56] also increases the average I/O ratio relative to buildings without those sources [47, 48, 53, 60, 70, 78–80], albeit to a lesser extent: 25% on average. In these cases, the ventilation system's filter efficiency plays a very significant role in limiting the penetration of outdoor particles: the I/O ratio in buildings that are equipped with high–efficiency filters were on the lower end of the spectrum, while buildings without any filter or with a low–efficiency or damaged one presented I/O ratios closer to those found in buildings that used natural ventilation [69, 80, 81].

In summary, the PM2.5 particles that are found in the indoor environment can be brought in by the ventilation airflow or can be internally generated by combustion for both heating and cooking. Table 5.1 presents the average ratios for naturally and mechanically ventilated buildings. As expected, the ratios for mechanically ventilated buildings are lower, although the difference is only substantial in the cases with significant internal particle sources.

5.1.2 Simulation of Indoor PM2.5 Levels

Increased awareness on the negative effects of PM2.5 in the built environment resulted in the development of several simulation approaches to predict indoor pollutant levels.

The simplest statistical approaches combine typical I/O ratios with a probabilistic window–use model [14, 82] and are the simplest method to assess indoor PM2.5 levels. In more sophisticated cases, these approaches may integrate land–use [83] and building–use models [84–87]. This approach does not consider several important factors that affect indoor PM2.5, such as changes in the ventilation airflow rate or the effect of different filtration efficiencies but allow for simple overall estimations of the average indoor PM2.5 levels of a sample of buildings [14].

In order to achieve higher precision in the prediction of PM2.5 levels in a specific building, detailed numerical models, such as CFD or nodal models, are the most common approach. These models take into account particle sources (including re–suspension), particle sinks (which includes the settling of particles onto surfaces), and the transport of particles by air movement between the outdoor and indoor environments and between indoor zones.

CFD models predict whole–field data (air velocity, pressure and PM2.5 concentration) for every simulation cell in the simulation domain, considering sources, sinks and the PM2.5 transport between cells. This allows for a detailed calculation of particle levels within the building, but at a very high computational cost. Consequently, CFD is typically used only when a detailed understanding of particle movement is necessary [88–93].

In the case of nodal models, a single node is attributed to each indoor zone or room, with additional nodes representing the outdoor environment in each ventilation opening or crack in the building's external surfaces. In each time step, these models can compute the current PM2.5 concentration of each node, by calculating the net sum of all sources, sinks and inter–node transport, which is then added to the PM2.5 concentration of the previous time step. This requires a more detailed input than the simplified approaches, resulting in a more thorough characterization of PM2.5 levels within the building. Nonetheless, this approach's computation cost is lower than CFD, due to the simplification of each zone into a single node.

Available nodal model approaches include both ad–hoc models that are developed for particular simulation cases [53, 94–101], and software packages, which can be used in different cases. Commonly used packages include CONTAM [102–105], MATLAB Simulink [106, 107] and the GCA, included within the EnergyPlus thermal simulation software package [108–111]. All of these software packages combine airflow and pollutant transport models.

Overall, nodal models, which include both ad–hoc models and software packages, are the most commonly used approach to simulate indoor PM2.5 levels, as they allow a thorough characterization of PM2.5 levels in the building with a low computational cost. Nonetheless, further model validation is essential to ensure meaningful results.

5.1.3 Minimizing Indoor Exposure to PM2.5

There are several solutions to limit the exposure to PM2.5 that have been proposed and implemented throughout the world. These solutions can be categorized in accordance to the method used to limit exposure: reducing outdoor PM2.5 sources, reducing indoor PM2.5 sources and reducing the penetration of outdoor PM2.5 into the indoor environment.

Traffic is one of the most significant sources of outdoor PM2.5 and, therefore, has been the focus of several efforts to decrease urban fine particle levels. Progressively stringent emission regulations have forced vehicle manufacturers to decrease the exhaust fume emission of PM2.5. This is achieved by the installation of particle filters, which reduces the direct emission into the atmosphere, and the increase in engine combustion efficiency, which decreases the emission of the gases that are precursors to the formation of secondary particles [112]. The use of cleaner fuels, such as biodiesel, low–sulfur gasoline or natural gas, also decreases precursor gas emissions [112–116], while vehicles without internal combustion engines do not emit either precursor gases or exhaust particles. Nonetheless, exhaust fumes are not the only source of PM2.5, and hence other measures have also been adopted. Paving unpaved roads, playgrounds, parking lots and other areas, in addition to street cleaning avoids the re–suspension of particles [61, 113, 117]. An increase in urban vegetation can decrease PM2.5 levels [113, 118], although failure to carefully plan the effect of that vegetation can compromise the effectiveness of this approach [119, 120]. Further, limiting vehicle circulation is becoming a common approach to decrease traffic–related PM2.5 emissions. In some locations, vehicles can only circulate every other day, depending on the license plate number [112, 117, 121]. More pollutant–emitting vehicles, such as older (and hence subject to less strict emission regulations) or heavy–duty diesel–powered vehicles, are only allowed to circulate during moments of low traffic intensity, such as at night or during the weekend, or not allowed at all [122–124]. The time–limited ban, however, might not decrease overall PM2.5 levels, especially if the PM2.5 that is emitted during the allowed periods remains in the atmosphere. In the future, it may happen that traffic will be banned altogether, with few exceptions, such as residents or emergency services. This leads to a shift to soft modes of transport, such as walking or bicycle–riding [125–127], or to public transport, which itself can be based on low PM2.5–emitting vehicles, such as electric trains or buses. In addition to the decrease in PM2.5 levels, this also brings forth several other additional benefits, such as the increase in physical activity and its consequential health benefits, and the decrease in traffic intensity, which itself reduces noise and traffic–related stress and incidents [125, 128].

Especially in places where industry and power generation are significant PM2.5 sources, several steps can be taken to decrease their negative impacts. In the case of industry, a shift to cleaner fuels and the use of particle filters decrease the emission of PM2.5 into the atmosphere [121, 128, 129]. Particle filters are also an option in fossil–fuel based power generation, but a shift to cleaner and renewable energy sources should be the main focus [112]. Additionally, limiting outdoor biomass combustion, such as straw burning, and wildfire prevention are fundamental steps to decrease overall urban PM2.5 emissions [112].

Controlling indoor PM2.5 sources is an essential step to reduce building occupant exposure to PM2.5. Firewood combustion for cooking and heating can be replaced with cleaner fuels, such as natural or liquefied petroleum gases (LPG), or with electric equipment [39, 42–44]. Alternatively, high–efficiency biomass–based heating systems with good extraction ventilation can also decrease PM2.5 emissions into the building [130, 131]. Different cooking methods and ingredients, such as preferring safflower oil over olive oil [132] or adding salt and pepper in the early stages of cooking [133], can also reduce the emission of PM2.5. Additionally, some ingredients might increase individual self–protection against the negative effects of PM2.5 [134]. Good extraction ventilation is also fundamental in the case of indoor sources that cannot be easily replaced or forgone, such as cooking or printers and similar devices [135]. Nonetheless, the use of the latter can be decreased by replacing paper with low power–consuming electronic devices [136]. Dust re–suspension can be prevented through cleaning, although, if done carelessly, it can lead to an increase in unwanted airborne PM2.5 levels due to re–suspension. Finally, portable air cleaners, which are devices that consist of a fan and a filter (either a high–efficiency cloth filter or an electrostatic filter [137–146] or even botanical elements [147]), actively decrease PM2.5 levels, by circulating indoor air through that filter. Portable air cleaner units equipped with High Efficiency Particulate Arrestance (HEPA) filters typically achieved the highest clean air delivery rates, while those with electrostatic filters usually had lower power consumptions, although they can increase indoor ozone and ultrafine particle levels [140, 143]. Additionally, the portable air cleaners' efficacy is sensible to its location within the building and to the interaction between its own airflow and that of other sources [148–150].

Finally, the building skin, as an interface between the indoor and outdoor environments, can also play a significant role in reducing indoor PM2.5 levels, by limiting the penetration of outdoor particles. First of all, careful urban planning can avoid buildings with sensitive occupants, such as schools or hospitals, to be located nearby main PM2.5 sources, such as high traffic–intensity highways [61, 151–153]. Additionally, moving people from slums to proper housing [152] and improving existing buildings' air tightness [154, 155] decreases the penetration of outdoor particles, including the re–entering of indoor–generated PM2.5 that has been extracted to the outdoor environment.

As for the building itself, one of the most commonly used methods is the use of a cloth filter in the MV system. A wide range of PM2.5 retention efficiencies can be found, with very high–efficiency (above 90%) filters being used in buildings with sensitive occupants, such as hospitals, or that, for some particular reason, require very low indoor PM2.5 levels [155, 156]. Nonetheless, higher filtration efficiencies imply a higher pressure drop through the filter, requiring a more power–consuming fan [157–159]. In the case of fossil–fuel based electric grids, this leads to an increase in PM2.5 emissions. Further, these filters' high pressure drop bars its use in natural ventilation systems. Ribbed air ducts can also decrease the transport of outdoor fine particles, although the effect on the airflow itself is yet to be addressed [160, 161]. Localized outdoor PM2.5 removal can also reduce the penetration of outdoor particles, although its application outside of semi–enclosed locations has not yet been considered [162]. Other filter technology, with high–efficiency particle removal and low pressure drops, has been proposed, although their widespread real–case use is yet to be developed [163–165].

Few approaches have been developed to allow the use of natural ventilation while simultaneously controlling for the penetration of outdoor PM2.5. One novel approach would be the use of electrostatic filters in natural ventilation openings. This type of filter is already used in several other applications and can achieve average PM2.5 filtration efficiencies of up to 63% [166–169] at a very low energy cost [170–172]. These filters consist of a channel with wire–electrodes that generate an electric field, which charges the airborne particles, and charged plates to separate those charged particles from the airflow. The pressure drop through this filter is less than 10 Pa, which could allow its use in natural ventilation. However, this approach has only been considered in simulated environments and lacks field testing as well.

Overall, limiting man–made combustion, namely by decreasing traffic or shifting to cleaner energy sources is the most efficient path for decreasing outdoor PM2.5. The use of cleaner energy sources indoors also decreases PM2.5 levels within the built environment, as does the use of effective extraction ventilation for indoor sources. To limit the penetration of outdoor PM2.5 through the incoming airflow, several innovative solutions are needed. Ultimately, one of the most important steps is to increase public awareness of PM2.5, encouraging people and national governments, on their behalf, to engage in these solutions as well as developing other solutions.

5.2 Methodology

The methodology used to study the effects of high levels of PM2.5 on the usability of natural ventilation is a detailed simulation analysis of the impact of NV on the HVAC electricity consumption and indoor PM2.5 exposure of an office building. This approach uses several years of measured hourly weather and PM2.5 data as input to a building thermal and airflow simulation model of a typical medium–size naturally ventilated office building. This methodology predicts the impact of PM2.5 and NV use in terms of occupant exposure and building HVAC electricity consumption. The simulation model that was used has four main components:

- The building geometry and material properties, to assess heat transfer.
- Equipment, lighting and occupant loads and schedules.
- Building HVAC and NV airflow model.
- Pollutant air transport model, to predict the penetration of outdoor PM2.5, deposition of particles onto surfaces, re–suspension from those surfaces and filtering by the HVAC system.

The next subsections describe the analysis approach in detail.

5.2.1 Weather and PM2.5 Data

This research focused on three regions throughout the world, which present contrasting difficulties regarding the usability of NV and the limiting effect of PM2.5 pollution: California (United States) [109], Europe [173] and Asia [111]. California is a state that has long been in the vanguard of renewable energy technologies and NV use in non–domestic buildings [174]. Five cities within the largest metropolitan areas in this State (Fig. 5.2) [175, 176] that account for nearly 90% of the state's population [177] were chosen: San Diego, Burbank, Fresno, Sacramento and Livermore. Overall, local climate is not especially challenging in California, with most of the temperature–related NV limitations occurring due to high temperatures during the summer season. However, the large populations in these urban areas might lead to high PM2.5 levels which could then limit the use of NV. Nonetheless, both the United States [178–180] and the state of California [181] have the strictest PM2.5 regulations among the regions assessed under this research, which can reduce that limiting effect.

In Europe, nine cities were selected (Fig. 5.2 [182]): Antwerp (Belgium), Krakow (Poland), Lisbon (Portugal), London (United Kingdom), Madrid (Spain), Paris (France), Prague (Czech Republic), Skopje (North Macedonia) and Strasbourg (France). These cities are the center of some of the largest urban areas in Europe that house and employ several million people each, leading to high particle levels, as discussed in several previous studies [183, 184]. Similarly to California, higher temperatures during part of the summer season might be a limitation to the use of NV. However, this region also faces a distinct challenge: very low temperatures during the winter can also disallow the use of NV in that season as well as possibly resulting in a need for mechanical heating. As for Lisbon and Madrid, the local climates are similar to those found in California and, thus, so are the predicted weather–related NV usability limitations.

Finally, in Asia, where previous studies have shown that high outdoor pollution can significantly hinder the use of NV [16], three of the five most populous megacities were chosen [2] (Fig. 5.2 [185]): Beijing and Shanghai, in China, and New Delhi, in India. These three cities are located in the most polluted regions of the world and rank among the twenty most polluted cities in the world (New Delhi tops the list [186]). In addition to high air pollution levels, local climate is also very warm and therefore challenging for passive cooling and ventilation systems. Clearly, in

Fig. 5.2 **A** Location of San Diego, Burbank, Fresno, Sacramento and Livermore, and transport of coarse particles by the Santa Ana winds in Southern California (lower left corner); **B** Location of Antwerp, Krakow, Lisbon, London, Madrid, Paris, Prague, Skopje and Strasbourg; **C** Location of Beijing, Shanghai and New Delhi

these three megacities, the use of NV to provide indoor comfortable conditions and acceptable indoor quality is difficult and requires innovative hybrid solutions that combine active and passive systems.

The selection of cities for each of these three regions was also conditioned by the availability of simultaneous hourly weather and PM2.5 data. Weather data was obtained from the Third Version of National Solar Radiation Database [187, 188] for California and New Delhi, the MACC–RAD [189] (solar radiation data) and the NCEI Integrated Surface Data [190] databases for Europe, and the White Box Technologies historical weather database [191] for Beijing and Shanghai. The California Air Resources Board [192] and the EEA AirBase [193] databases provided the PM2.5 data for California and Europe, while data for China [194] and India [195] was obtained via the U.S. Department of State Air Quality Monitoring Programs in those two countries. The weather datasets consisted of an hourly record of dry bulb and dew point temperatures, relative humidity, atmospheric pressure, wind speed and direction, and direct beam, diffuse horizontal and global horizontal solar radiation. The datasets for California and Asia, as well as the solar radiation dataset for Europe were complete. However, data was missing for a limited set of time steps in the European weather database and in all PM2.5 databases. In order to limit the impact of missing PM2.5 data, in cities with at least two PM2.5 measuring stations, all available stations in each city were taken into account and their measurements were averaged, at each timestamp (considering the number of stations available).

In order to minimize the uncertainties that would arise from large data gaps, only city–year datasets with less than 10% of missing PM2.5 measurements and a maximum consecutive gap of 5 weather measurements (only applicable to Europe) were considered. Further, linear interpolation was used to complete the dataset for gaps of less than 24 h [196]. In the case of longer gaps, simulation results, i.e. cumulative indoor PM2.5 exposure and HVAC electricity consumption, were ignored for those periods and compensated by extrapolation of the remaining results. The city–year datasets that were used in the detailed simulation analysis are shown in Table 5.2.

5.2.2 Detailed Simulation Analysis

The building model used in the detailed simulation analysis was based on the Medium Office Model of the standard United States Department of Energy Commercial Reference Buildings dataset [197]. Only the middle level of the three–story reference building was kept, with the ceiling and floor plates connected to create periodic boundary conditions [198] (Fig. 5.3). This approach simplifies the simulation at the expense of ignoring boundary effects on the first and last levels. Whenever the top floor is well insulated, this approximation is conservative, since the expected cooling thermal demand from the top and bottom floors can be lower than the middle floors due to increased ceiling (top level) and floor (ground level) slab thermal inertia.

Table 5.2 Years used in the detailed hourly simulation analysis

City	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
San Diego			●	●	●	●	●			
Burbank					●	●	●			
Fresno	●	●	●	●	●	●	●			
Sacramento	●	●	●	●		●	●			
Livermore	●	●	●	●	●		●			
Antwerp								●		
Krakow				●	●	●	●	●		
Lisbon	●	●		●	●	●	●	●		
London	●	●		●	●	●	●	●		
Madrid		●		●	●	●		●		
Paris								●		
Prague	●	●		●	●	●		●		
Skopje								●		
Strasbourg								●		
Beijing						●	●	●	●	●
Shanghai								●	●	●
New Delhi									●	●

The standard version of the Medium Office Model does not allow for optimal use of NV in all the floor plan since part of the occupied area was more than 6.096 m from an opening (the maximum depth that can be naturally ventilated with windows in a single façade, according to the California Mechanical Code). To facilitate NV use, the original building model was adapted, obtaining a building that, when weather conditions allow, can be fully naturally ventilated, in addition to an improved passive thermal behavior (building construction details are shown in [111, 173, 174]), and full compliance with state and federal regulations [199–204]. Indoor thermal mass was set to an equivalent of two 10 cm wooden layers throughout the office zones [205], while outdoor air infiltration was defined as 0.00136 $m^3\ s^{-1}$ per square meter of external area [206] (Table 5.8).

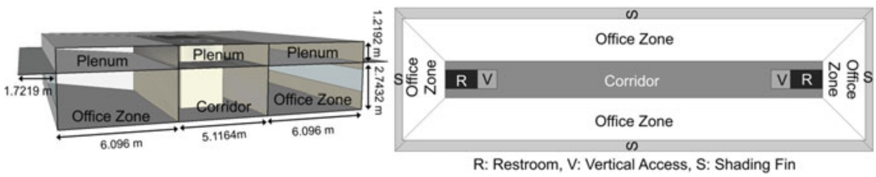

Fig. 5.3 Building simulation model section cut and zones

5.2.3 Equipment, Lighting and Occupant Loads

Occupant metabolic and latent heat, lighting and office equipment all contribute to the thermal load that must be removed by the cooling system. To accurately define each of these thermal loads, the open plan office area was divided into individual workspaces with 11.6 m^2 of floor area, a typical value for an office. In a typical office, not all workspaces are in use during the whole day. The hourly occupation used in the simulations followed an average measured weekday office occupation profile [207].

Light power density was set to the California Energy Code's maximum requirements, at 8.07 W/m^2 in the office zones and at 6.46 W/m^2 in the remaining zones. During the unoccupied hours (nighttime, holidays and weekends), light power density was reduced to 25% in all zones [136]. Office equipment power density was based on Johnston et al. [136] and averaged 9.74 W/m^2 [136, 208]. In the unoccupied periods, this power load was reduced by approximately 71% [136].

5.2.4 HVAC Model

The model's HVAC system includes a rooftop air handling unit (AHU) with an integrated heat pump (Fig. 5.4). In order to meet the requirements of the California Mechanical Code's air renewal requirements, this system provides outdoor air at the rate of 8.5 m^3 per hour and per person and 1.1 $m^3\ h^{-1}\ m^{-2}$, with a total inflow and exhaust fan pressure drop of 1438 Pa and an average fan efficiency of 50.1% [209].

Two HVAC set point scenarios were used, according to the availability of PCS:

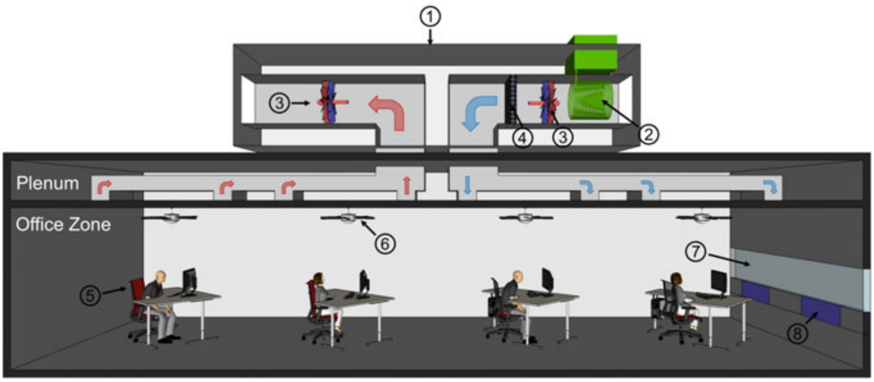

Fig. 5.4 HVAC layout: (1) Rooftop air handling unit; (2) Heat pump and heat exchanger; (3) Fans; (4) Cloth filter; (5) Heated chair; (6) Ceiling fan; (7) Window; (8) NV electrostatic filter

- SC: the HVAC system alone maintains the building indoor temperature between 20 and 26 °C, the recommendations of the ISO 7730:2005 standard for a category B office [29].
- EC: the HVAC system maintains the building indoor temperature between 18 and 30 °C. This extended temperature range is due to the existence of PCS that supplement the AHU, namely heated chairs and ceiling fans, which were chosen in order to allow the same predicted comfort levels. Heated chairs are in operation when occupied and if the zone temperature drops below 20 °C [34]. Ceiling fans provide an additional cooling effect whenever the zone temperature is above 26 °C [31].

At each simulation time step, a coefficient of performance (COP) was calculated to predict the energy consumption of the rooftop AHU, which is a function of the heat pump's evaporator and condenser temperatures and the heat pump's efficiency (ψ) (Eqs. (5.1) and (5.2)).

$$\mathrm{COP_{heat}} = \psi_{\mathrm{heat}} \times \frac{\mathrm{T_{cond}} + 273.15}{\mathrm{T_{cond}} - \mathrm{T_{evap}}} \tag{5.1}$$

$$\mathrm{COP_{cool}} = \psi_{\mathrm{cool}} \times \frac{\mathrm{T_{evap}} + 273.15}{\mathrm{T_{cond}} - \mathrm{T_{evap}}} \tag{5.2}$$

When in heating operation, the heat pump's condenser temperature was set to 50 °C, while the evaporator temperature was set to 5 °C below the outdoor temperature. When in cooling mode, those temperatures were 5 °C above the outdoor temperature and 0 °C, respectively [9].

The heat pump's efficiency is the ratio between its actual *COP* and that of an ideal Carnot engine and was considered to be 40% [210]. The AHU was equipped with a heat recovery system with an efficiency of 80% [211], although it was only used in Europe and Asia, where heating needs were higher. Further, 10% of the produced heat load was considered lost in the distribution system, while the electric consumption was increased by 10% to account for the consumption of the water circulation pumps [9]. Finally, the electric energy required to power the fan was calculated with Eq. (5.3).

$$\mathrm{E_{vent}} = \frac{\mathrm{p_{vent}} \times \dot{\mathrm{V}}_{\mathrm{vent}}}{\eta_{\mathrm{vent}}} \tag{5.3}$$

The heating, cooling and ventilation annual energy consumption of this developed simulation model was compared with the results of the Californian Commercial End–Use Survey [212], a database that presents the energy consumption of several non–domestic building types. The model's energy load was found to be within the range for office buildings (Table 5.3).

Table 5.3 Validation of HVAC electricity consumption

Parameter (kW h m^{-2} $year^{-1}$)	Simulation model	Database
Cooling	36	28–38
Heating	5	2–5
Ventilation	16	14–33

Nevertheless, the original simulation model was modified as described above to improve its passive thermal behavior and equipment efficiency, allowing a 60–75% decrease in overall HVAC energy consumption.

5.2.5 Modeling of Single–Sided NV

The use of NV leads to energy savings that can be quantified as the difference in the building's yearly HVAC electricity consumption with NV and without NV. In both HVAC set point scenarios, the following two NV–use scenarios were used to quantify these two cases:

- NoNV: Mechanical ventilation is in operation during all working hours. NV is not used.
- NVP: Hybrid natural/mechanical ventilation is available during all working hours. In each of the four office zones and at each time step, windows are opened (Table 5.4), as NV replaces the centralized HVAC system if the outdoor temperature is between 10 °C and that zone's air temperature. Further, if the outdoor temperature is above 26 °C, NV is only available if the outdoor relative humidity is below 80%. During the unoccupied hours, namely at night and during weekends and holidays, NV is available with the same constraints.

Two approaches were proposed to limit the increase in occupant exposure to PM2.5 that results from the use of NV: limiting its use to moments of low outdoor PM2.5 concentrations and using an electrostatic filter (ESF) to limit the transport of PM2.5 by the naturally ventilated airflow:

- NVS: same temperature criteria as NVP. However, windows are only opened if the outdoor PM2.5 concentration is below the following thresholds:

Table 5.4 Indoor climate control systems used in the detailed simulation approach

Indoor Climate Control System	SC				EC			
	NoNV	NVP	NVS	NVF	NoNV	NVP	NVS	NVF
Rooftop air handling unit	●	●	●	●	●	●	●	●
PCS					●	●	●	●
Operable windows		●	●			●	●	
ESF				●				●

– California (NV12): 12 μg/m^3 [178–181];
– Europe (NV10): 10 μg/m^3 [46].
– Asia, two thresholds were considered (NV10 and NV35, respectively): 10 and 35 μg/m^3 [46].

- NVF: same NV–use criteria as NVP. When NV is used, openings equipped with an ESF (described in Sect. 5.2.6) are used instead of windows (Table 5.4).

Table 5.4 shows a summary of the systems used in the eight scenarios considered in the detailed simulation analysis.

The model considers wind and buoyancy–driven single–sided natural ventilation [213]. In the case of wind–driven NV, a typical urban wind profile was used to reduce the wind speed profile in the measured weather data [208].

In each office zone, the maximum openable window area is 5% of its gross floor area, which is equivalent to a window–to–wall ratio (WWR) of 3.5% for the two larger office zones and 2.5% for two smaller office zones). Nonetheless, window opening area has been shown to increase linearly with the outdoor temperature, while never reaching a completely open position [214]. Thus, the opening area was considered to range from 1% of the floor area, for an outdoor temperature of 10 °C, to 3.5%, for 30 °C, as given by Eq. (5.4):

$$A_{open} = A_{open,\,max} \times (0.0242 \times T_{out} - 0.037) \tag{5.4}$$

5.2.6 *Pollutant Transport Model*

The prediction of internal PM2.5 levels was performed with a modified version of the GCA that is available in the building thermal simulation tool that was used for this research (EnergyPlus). The standard version of the GCA cannot model the reduction in the transport of outdoor pollutants into the building that results from both the settling of PM2.5 transported by the infiltration airflow within building cracks and the incorporation of a fine particle filter in the rooftop AHU. To overcome this limitation, the standard GCA model equation was modified and implemented in a custom version of EnergyPlus. Equation (5.5) is a term of the GCA equation which refers to the transport of outdoor pollutant by the infiltration airflow: if the outdoor particle concentration is higher than within the simulation zone, more polluted air is entering the building; if not, the infiltration airflow is introducing cleaner air. Equation (5.6) shows the change that was applied: the outdoor particle concentration is corrected by the particle penetration rate, which was considered to be 80% [108].

$$\dot{m}_{inf} \times (K_{out} - K_z) \tag{5.5}$$

$$\dot{m}_{inf} \times (F \times K_{out} - K_z) \tag{5.6}$$

Further, the term that models the transport of outdoor pollutant by the ventilation supply duct into the simulation zone is shown in Eq. (5.7): if the particle concentration is larger in the supply duct than in the simulation zone, the ventilation system is introducing air with a higher pollutant concentration; if not, the system is introducing cleaner air. Equation (5.8) shows the change that was applied: the particle concentration in the supply duct is corrected by a factor which takes the filter's efficiency into account. This was considered to be a MERV 14–grade filter (equivalent to an F8–grade filter [215]), which has an effective PM2.5 removal efficiency of 71.4% [25] and which was kept constant throughout the simulation, as high–efficiency filters are usually not affected by particle loading during use [216, 217].

$$\dot{m}_{sys} \times \left(K_{sup} - K_z\right) \tag{5.7}$$

$$\dot{m}_{sys} \times \left([1 - \eta_{HVACfilter}] \times K_{sup} - K_z\right) \tag{5.8}$$

Additionally, the deposition rate on indoor surfaces was set to 0.19 h^{-1} [108] and the occupant–induced re–suspension obtained in Thatcher and Layton [96] was used. Both parameters are constant throughout the simulation, due to the difficulty in accurately modeling their change through time, an approach followed by other studies [108, 217]. Further, the floor loading, which affects the re–suspension rate, is based on a surface area that is 60% hard floor and 40% carpet that are each equally distributed between tracked and untracked surfaces.

A further modification to the GCA model equation was required to model the effect of the electrostatic filter that was used in the NVF scenario. The term in Eq. (5.9) refers to the pollutant transport into the simulation zone from the outside by the naturally ventilated airflow. The change that was applied is shown in Eq. (5.10): the outdoor particle concentration is corrected by a factor that considers the electrostatic filter's efficiency into account.

$$\dot{m}_{nat} \times (K_{out} - K_z) \tag{5.9}$$

$$\dot{m}_{nat} \times ([1 - \eta_{NVfilter}] \times K_{out} - K_z) \tag{5.10}$$

This filter has an effective PM2.5 removal efficiency of 63%, which was kept constant in the simulation, assuming regular cleaning [167]. A voltage of 27.5 kV is required for filter operation, while the electrical current is assumed to be proportional to the PM2.5 mass flow rate through the filter and was calculated as 26.5 μA per unit μg/s, totaling a power consumption of 0.73 W s/μg).

5.3 Results and Analysis

The results of the detailed simulation analysis are summarized by the ratio between the yearly energy savings (Δe) and the increase in cumulative exposure to PM2.5 of outdoor origin (ΔP), in order to quantify the trade–off between energy savings and increased exposure.

5.3.1 Energy Savings

The annual electricity consumption of the HVAC system for each NV–use scenario is shown in Fig. 5.5 (California), Fig. 5.6 (Europe) and Fig. 5.7 (Asia):

- NoNV: this scenario's electricity consumption is given by the sum of the four bars (red, black, blue and green).
- NVS: the sum of the blue, black and red bars is this scenario's electricity consumption; green is the energy that is saved.
- NVF: the electricity consumption is the sum of the red and black bars; the black bar is the electricity consumption of the electrostatic filters; the sum of green and blue is this scenario's energy savings.
- NVP: the red bar gives the electricity consumption; the sum of all other bars is this scenario's energy savings.

Table 5.5 presents the yearly HVAC energy savings for each NV–use scenario relative to each NoNV scenario.

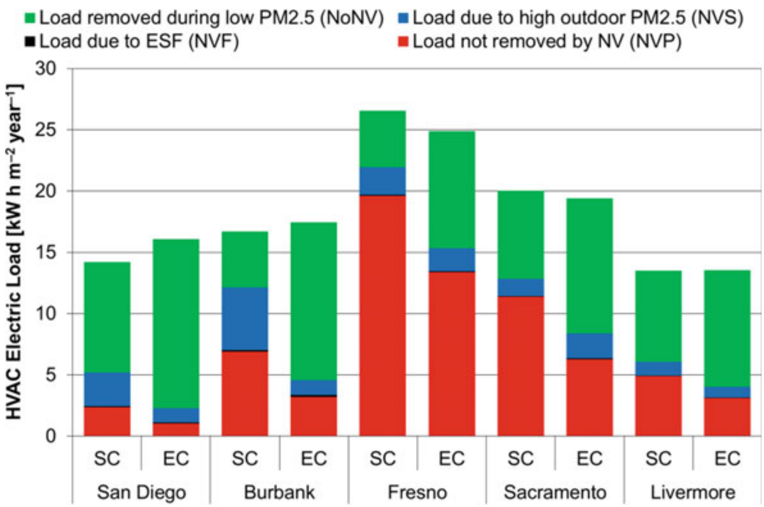

Fig. 5.5 Yearly HVAC electric load for each NV–use scenario in California

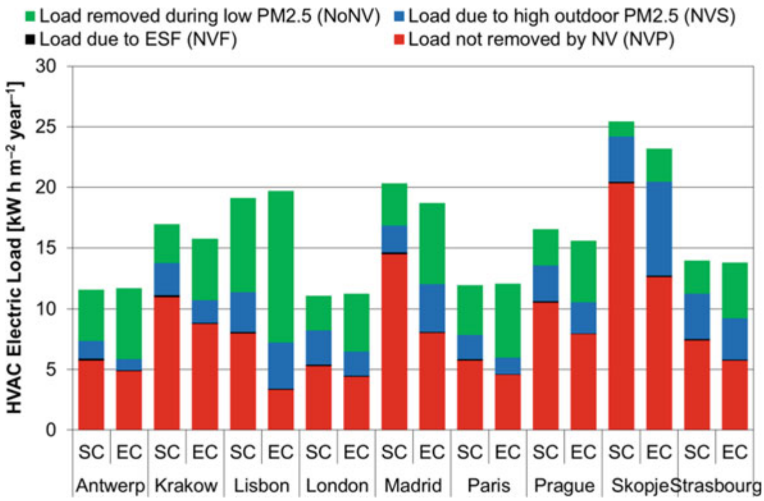

Fig. 5.6 Yearly HVAC electric load for each NV–use scenario in Europe

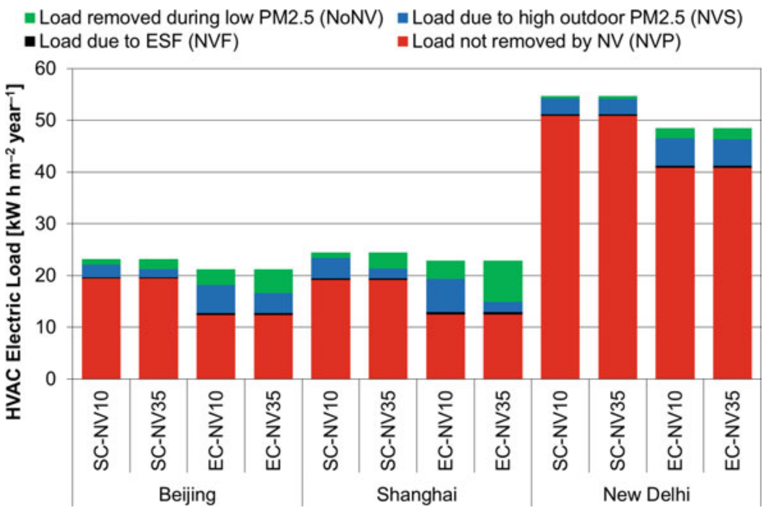

Fig. 5.7 Yearly HVAC electric load for each NV–use scenario in Asia

As expected, for each HVAC set point scenario, the NoNV scenario results in the highest energy consumption. On the opposite end is the NVP scenario, where HVAC electricity consumption is reduced by the replacement of mechanical ventilation and cooling by natural ventilation that introduces cooler air into the building. In California, using NV whenever it can provide a cooling effect decreases the HVAC consumption by 26–83% with SC criteria. However, if NV is only used when PM2.5 levels are low, savings decrease to between 17 and 63%. The availability of PCS

Table 5.5 Average yearly HVAC energy savings (absolute [kW h m^{-2} $year^{-1}$] and relative [%] decrease) for each NV–use scenario relative to each NoNV scenario

City	SC			EC		
	NVP[a]	NVF[a]	NVS[a]	NVP[a]	NVF[a]	NVS[a]
San Diego	11.8; 83	11.7; 83	9.0; 63	15.0; 93	14.9; 93	13.8; 86
Burbank	9.8; 59	9.7; 58	4.5; 27	14.2; 82	14.1; 81	12.8; 74
Fresno	6.9; 26	6.8; 26	4.6; 17	11.5; 46	11.4; 46	9.5; 38
Sacramento	8.6; 43	8.6; 43	7.1; 36	13.1; 68	13.0; 67	11.0; 57
Livermore	8.5; 63	8.5; 63	7.4; 55	10.4; 77	10.3; 76	9.5; 70
Antwerp	5.8; 50	5.7; 49	4.2; 36	6.8; 58	6.7; 57	5.8; 50
Krakow	5.9; 35	5.8; 34	3.1; 19	6.9; 44	6.8; 43	5.0; 32
Lisbon	11.1; 58	11.0; 57	7.7; 40	16.3; 83	16.2; 83	12.4; 63
London	5.8; 52	5.6; 51	2.8; 25	6.8; 61	6.7; 60	4.8; 42
Madrid	5.8; 29	5.6; 28	3.4; 17	10.7; 57	10.6; 57	6.6; 35
Paris	6.2; 52	6.1; 51	4.1; 34	7.5; 62	7.4; 61	6.1; 50
Prague	6.0; 36	5.9; 35	2.9; 18	7.6; 49	7.5; 48	5.0; 32
Skopje	5.0; 20	4.9; 19	1.2; 5	10.5; 45	10.4; 45	2.7; 12
Strasbourg	6.6; 47	6.5; 46	2.7; 19	8.0; 58	8.0; 58	4.6; 33
Beijing (NV10; NV35)	3.7; 16	3.5; 15	1.0; 5; 1.9; 8	8.8; 41	8.4; 40	2.9; 14; 4.6; 22
Shanghai (NV10; NV35)	5.2; 21	4.9; 20	1.0; 4; 3.0; 12	10.3; 45	9.9; 43	3.4; 15; 7.9; 35
New Delhi (NV10; NV35)	3.7; 7	3.5; 6	0.4; 1; 0.5; 1	7.6; 16	7.1; 15	1.9; 4; 2.1; 4

[a]The % only applies to the second number (to the right of the semi-colon)

in the NoNV scenario leads to a 3–7% decrease in HVAC consumption in Sacramento and Fresno and to a 4–13% increase in San Diego and Burbank. In Livermore, the effect is negligible. These low differences are due to the heated chairs' and ceiling fans' (mainly the latter) power load nearly offsetting the decrease in the rooftop AHU's already optimized consumption due to the building's improved passive thermal behavior. Nonetheless, the most significant advantage of these PCS is the higher NV availability, resulting in a higher reduction in HVAC electricity consumption: NVP savings increase to up to 93% and NVS savings up to 86%. Using both SC and EC criteria, the energy savings of the NVF scenarios are nearly identical to those of NVP, due to the electrostatic filter's very low energy consumption.

In Europe, the higher need for heating and the lower overall availability of NV result in a lower energy saving potential of the NVP scenario: 20–58% with SC criteria. High outdoor PM2.5 has a more limiting effect in this region than in California, with the NVS scenario leading to energy savings between 5 and 40%. The effect of PCS on the NoNV scenarios is, similarly to California, low: 1–8% savings in Strasbourg, Prague, Krakow, Madrid and Skopje, and 1–3% energy consumption increases in Paris, Antwerp, London and Lisbon. Again, EC criteria allow a higher NV availability and, consequentially, higher energy savings: up to 83% for NVP and up to 63% for NVS. The higher PM2.5 levels result in a slightly higher ESF electricity consumption. However, this consumption is still nearly negligible, thus the energy savings of the NVF scenario are similar to that of NVP.

PCS without NV lead to a 6–11% decrease of the annual HVAC electricity load in Asia. In the SC scenario, NVP reduces the annual HVAC consumption by 7% in New Delhi, 16% in Beijing and 21% in Shanghai. These low annual savings are mostly due to severe seasonal limitations in the use of NV in all three cities. In New Delhi, where most of the year is excessively warm for NV, its use leads to energy savings above 65% in the cooler months (December to February). However, between April and October, savings are nearly inexistent, leading to the overall low annual savings. In Shanghai and Beijing, where winters are too cold and summers are too warm, most savings occur during the mid–season. With EC criteria, the increased availability of NV increases the HVAC energy savings: 16% in New Delhi, 41% in Beijing and 45% in Shanghai. In New Delhi, NV allows savings above 50% between November and March, although during the remaining months, outdoor temperatures are still too high to allow any significant energy savings. In Beijing, most savings still occur during the mid–season, although a higher share of the yearly decrease in electricity consumption now occurs during the summer. In Shanghai, no seasonal change occurred, with most savings due to the use of NV still befalling on the mid–season. Restricting the use of NV to moments with outdoor PM2.5 levels below 10 $\mu g/m^3$ (NV10) leads to the lowest energy savings: 1–5% with SC criteria, 4–15% with EC. Since there is very low availability of NV during working hours, most of these savings occur due to the use of NV during the unoccupied period, which preemptively cools the building before its occupation. Despite its less restrictive threshold (35 $\mu g/m^3$), the NV35 scenario with SC criteria does not result in a substantial increase in savings: 1–12%. However, with EC criteria, savings are increased to 22% in Beijing and 35% in Shanghai. In New Delhi, savings are still remarkably low: 4%. Finally, the use of an electrostatic filter (NVF) leads to savings similar to those found in the NVP scenario, differing only due to the filter's low electric consumption.

5.3.2 Increased Cumulative Exposure to PM2.5

The increase in cumulative indoor exposure to PM2.5 of outdoor origin is presented on the left side of Fig. 5.8 (California), Fig. 5.9 (Europe) and Fig. 5.10 (Asia). The green bar is the exposure in case of the NoNV scenario. The additional bars represent the increase in cumulative exposure for each of the three scenarios, in growing order: black for NVF, blue for NVS and red for NVP. The vertical axis units are mg h m^{-3} $year^{-1}$ (instead of μg h m^{-3} $year^{-1}$) to reduce the number of trailing zeros on the axis labels. On the right side of the same figures, each point gives the average annual indoor PM2.5 concentration during working hours, for each city and

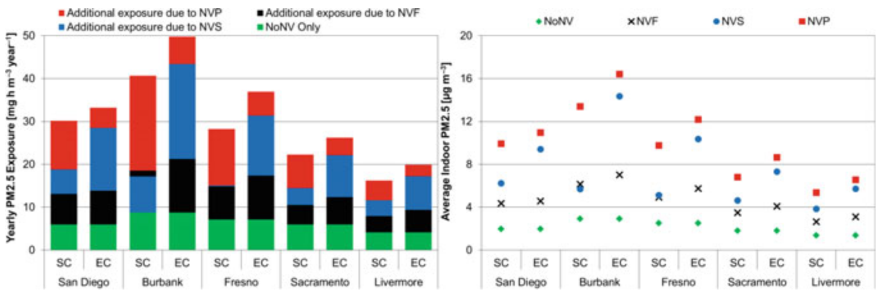

Fig. 5.8 Yearly cumulative exposure to PM2.5 and average indoor concentration for each NV–use scenario in California

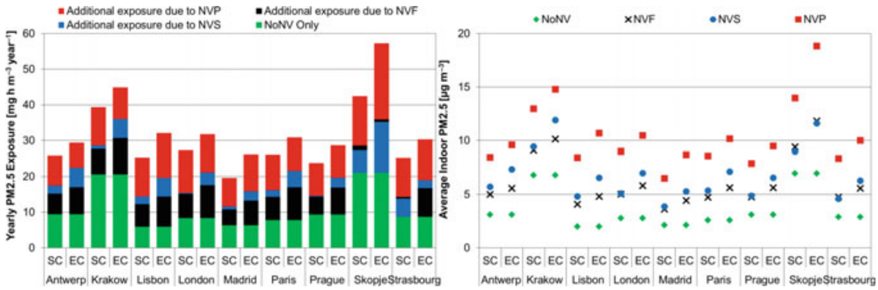

Fig. 5.9 Yearly cumulative exposure to PM2.5 and average indoor concentration for each NV–use scenario in Europe

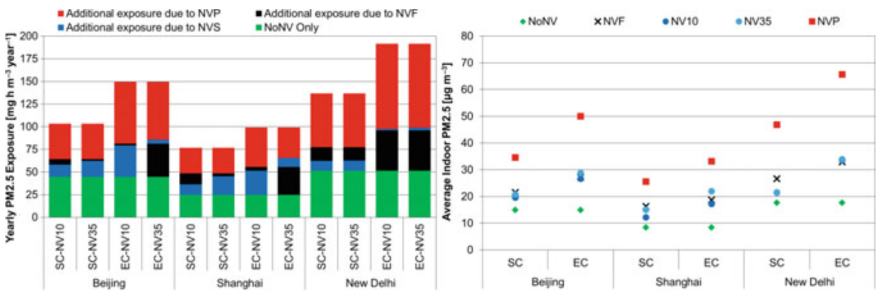

Fig. 5.10 Yearly cumulative exposure to PM2.5 and average indoor concentration for each NV–use scenario in Asia

NV–use scenario, with the same coloring scheme: green for NoNV, black for NVF, blue for NVS and red for NVP. Table 5.6 presents the increase in yearly cumulative exposure to PM2.5 for each NV–use scenario relative to the NoNV scenario.

Expectedly, the full–time use of a high–efficiency cloth filter leads to the lowest cumulative exposure to PM2.5 in the NoNV scenarios. On the opposite end is the NVP scenario, which allows the use of NV whenever possible, allowing PM2.5 to

Table 5.6 Average increase in yearly cumulative exposure to PM2.5 (absolute [mg h m^{-3} year^{-1}] and relative increase) for each NV–use scenario relative to the NoNV scenario

City	SC			EC		
	NVP	NVF	NVS	NVP	NVF	NVS
San Diego	24; 5.0×	13; 2.2×	7; 3.2×	27; 5.5×	23; 2.3×	8; 4.8×
Burbank	32; 4.6×	8; 2.1×	10; 2.0×	41; 5.7×	35; 2.4×	12; 4.9×
Fresno	21; 3.9×	8; 2.1×	8; 2.1×	30; 5.2×	24; 2.4×	10; 4.4×
Sacramento	16; 3.7×	9; 1.8×	5; 2.4×	20; 4.4×	16; 2.1×	6; 3.7×
Livermore	12; 3.9×	7; 1.9×	4; 2.8×	16; 4.8×	13 2.3×	5; 4.2×
Antwerp	16; 2.7×	8; 1.6×	6; 1.8×	20; 3.1×	13; 1.8×	8; 2.4×
Krakow	19; 1.9×	8; 1.3×	7; 1.4×	24; 2.2×	15; 1.5×	10; 1.8×
Lisbon	19; 4.2×	8; 2.1×	6; 2.4×	26; 5.4×	14; 2.4×	8; 3.3×
London	19; 3.2×	7; 1.×	7; 1.8×	23; 3.8×	13; 2.1×	9; 2.5×
Madrid	13; 3.1×	5; 1.7×	5; 1.8×	20; 4.1×	10; 2.1×	7; 2.5×
Paris	18; 3.3×	8; 1.8×	7; 2.1×	23; 3.9×	14; 2.2×	9; 2.8×
Prague	14; 2.5×	5; 1.5×	5; 1.6×	19; 3.1×	10; 1.8×	8; 2.1×
Skopje	21; 2.0×	6; 1.4×	7; 1.3×	36; 2.7×	14; 1.7×	15; 1.7×
Strasbourg	16; 2.9×	5; 1.6×	6; 1.6×	22; 3.5×	10; 1.9×	8; 2.2×
Beijing (NV10; NV35)	59; 2.3×	20; 1.4×	14; 1.3 × ; 18; 1.4×	105; 3.3×	37; 1.8×	35; 1.8 × ; 41; 1.9×
Shanghai (NV10; NV35)	51; 3.0×	24; 1.9×	11; 1.4 × ; 20; 1.8×	74; 3.9×	31; 2.2×	26; 2.1 × ; 41; 2.6×
New Delhi (NV10; NV35)	85; 2.7×	26; 1.5×	11; 1.2 × ; 11; 1.2×	140; 3.7×	45; 1.9×	46; 1.9 × ; 47; 1.9×

frequently enter the indoor environment without any obstruction, increasing exposure to between 3.7 and 5.0 the NoNV exposure levels, with SC criteria, in California. The extended use of NV that occurs as a consequence of the availability of PCS furthers that exposure increase: 4.4 to 5.7 times the exposures found in the NoNV scenario. Both limiting the use of NV to moments of low outdoor PM2.5 levels (NVS) and using NV whenever possible with an ESF (NVF) lead to intermediate exposure levels. Nonetheless, in most Californian cities, NVF leads to lower increased cumulative exposure (up to 2.2 times the NoNV levels for SC, up to 2.4 for EC) than NVS (up to 3.2 for SC and up to 4.9 for EC). Exceptions are Burbank, where NVS exposure is lower than NVF exposure, and Fresno, where cumulative exposure levels are similar (both with SC criteria).

Using NV whenever possible leads (NVP) to an average indoor PM2.5 concentration above the regulated state and federal levels (12 μg/m^3) in Burbank (both with SC and EC criteria) and Fresno (EC only). Also in Burbank, NVS with EC criteria also results in an average indoor concentration above 12 μg/m^3. All other scenarios do not exceed this limit in California.

In Europe, the maximized use of NV (NVP) increases occupant exposure by 1.9–4.2 times the NoNV levels with SC criteria and 2.2 to 5.4 with EC. These increases are lower than those found in California, although NV availability is also lower in this region. In most cities, the cumulative exposure levels that result from the NVF scenario are lower than with NVS: an increase of up to 2.1 for SC and up to 2.4 for EC, as opposed to up to 2.4 and up to 3.3, respectively. Exceptions are Skopje (both SC and EC criteria), Prague (SC only) and Strasbourg (SC only), where NVF and NVS exposure levels are nearly identical.

Average indoor PM2.5 concentrations exceed the WHO's guideline for PM2.5 exposure (10 $\mu g/m^3$) with NVP in several cities, especially with the increased availability of NV with PCS (EC criteria): Krakow (also with SC criteria), Lisbon, London, Paris, Skopje (also with SC) and Strasbourg. Additionally, in both Krakow and Skopje, the two exposure control approaches (NVS and NVF) fail to decrease the average indoor PM2.5 to below the WHO guideline, when PCS are available.

In Asia, NVP increases occupant exposure by 2.3–3.0 times the NoNV exposure levels if PCS are not available and by 3.3–3.9 if they are. These increases are similar to those found in many cities in Europe, despite the lower NV availability. Limiting the availability of NV (NVS) leads to similar cumulative exposure levels with both thresholds (10 and 35 $\mu g/m^3$): up to 1.4 and up to 1.8 times the NoNV exposure, respectively, with SC criteria, and up to 2.1 and 2.6 times, with EC criteria. Limiting the penetration of outdoor PM2.5 with an ESF results in exposure levels similar to the two NVS scenarios in both Chinese cities (up to 1.9 times the NoNV exposure levels for SC, up to 2.2 for EC) and in New Delhi if PCS are available (1.9 times the NoNV levels). In the Indian city, if PCS are not available, NVF increases exposure to only 1.2 times the NoNV exposure, although this is a consequence of the very low availability and use of NV (1.2 times).

Shanghai is the only Asian city where the indoor average PM2.5 concentration is below the WHO's guideline of 10 $\mu g/m^3$, although only when the HVAC system (and its high–efficiency cloth filter) is in full–time operation. Also in this city, the average indoor concentration that result from the NVP scenarios are below the WHO's first interim target (35 $\mu g/m^3$). In both other cities, using NV whenever possible exceeds this threshold, although both the NVS and NVF exposure control approaches decrease the indoor PM2.5 concentration to below that level.

5.3.3 Ratio Between Energy Savings and Increased Exposure

With the goal of quantifying the trade–off between energy savings and increased exposure, the ratio between the yearly energy savings (Δe) and the increase in cumulative exposure to PM2.5 of outdoor origin (ΔP) was calculated for each location and NV–use scenario. The most NV–favorable cities and scenarios will have the highest value of this indicator, since lower increases in particle levels for similar energy savings indicate that the combined weather and outdoor PM2.5 level conditions are more favorable to the use of NV. Further, comparing the results between the NVP and the NVS scenarios can show when natural ventilation is being used: a higher ratio in the NVS scenario indicates a higher use of natural ventilation when PM2.5 levels are low. The results are presented in Fig. 5.11 for California, Fig. 5.12 for Europe, Fig. 5.13 for Asia and, finally, in Table 5.7 for all cities.

In the case of the NVP scenario with SC criteria, Fresno (0.33) and Burbank (0.31) show the lowest value among the Californian cities: Fresno has the lowest energy savings, while Burbank has the highest increase in exposure. On the other hand, this indicator is highest in Livermore (0.71), due to the lowest increase in exposure. Energy savings and increased exposure are lower in the NVS scenario, as expected. In all cities, the $\Delta e/\Delta P$ ratio increases, as natural ventilation is mostly used in moments with low outdoor PM2.5 concentrations. This ratio is highest in the NVF scenario. This is the result of taking advantage of the available energy saving potential (energy savings are similar to the NVP scenario), in addition to the electrostatic filter limiting occupant exposure to PM2.5 to levels similar to or below those of the NVS scenario. Despite some minor differences, the same pattern can be seen with EC criteria.

In Europe, the order of magnitude of the $\Delta e/\Delta P$ ratio is similar to California. Lisbon presents the highest indicator value, at 0.58, when NV is used whenever possible (NVP), with SC criteria. In all other cities, the $\Delta e/\Delta P$ ratio ranges from 0.30 to 0.41. Lisbon is also the city with the highest $\Delta e/\Delta P$ value in the NVS scenario (0.63). Skopje is the only city where this ratio decreases for this NV–use scenario, as most energy savings occur during moments of high pollution levels. Again, the $\Delta e/\Delta P$ ratio is highest when an electrostatic filter is used to limit the penetration of outdoor PM2.5, at a very low energy cost (NVF).

With EC criteria, the ratio decreases for most cities, except for Lisbon, Madrid and Skopje. These three cities have the highest increase in NV availability when PCS

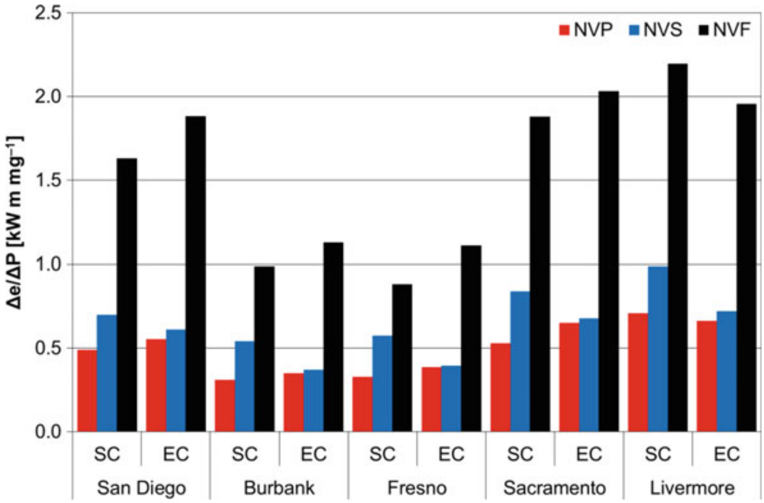

Fig. 5.11 Ratio between average energy savings and increase in PM2.5 exposure [kW m/mg] for each NV–use scenario in California

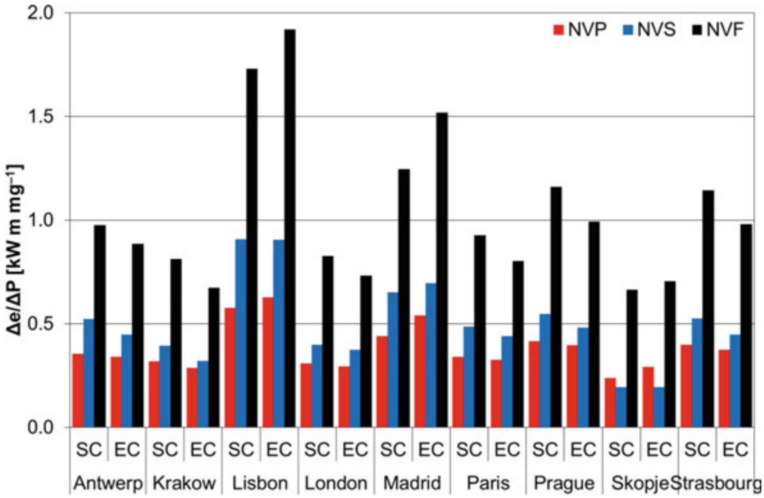

Fig. 5.12 Ratio between average energy savings and increase in PM2.5 exposure [kW m/mg] for each NV–use scenario in Europe

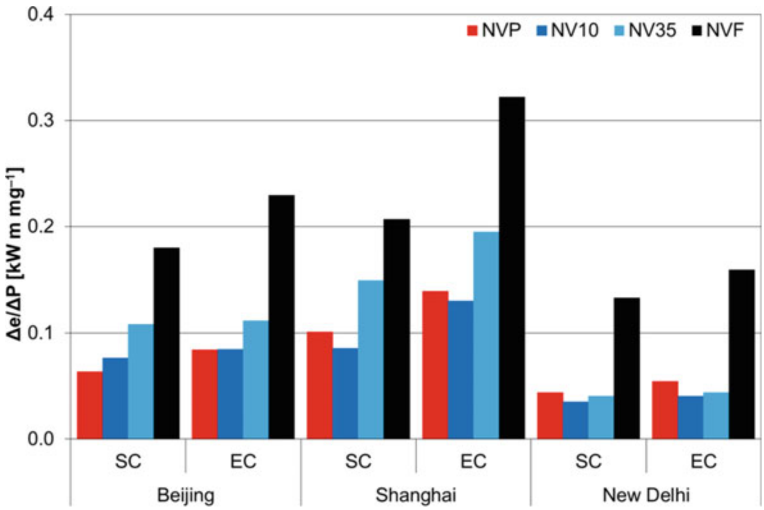

Fig. 5.13 Ratio between average energy savings and increase in PM2.5 exposure [kW m/mg] for each NV–use scenario in Asia

are available. Elsewhere, the low increase in NV potential results in an increase in exposure than is higher than the increase in energy savings.

In the NVP scenario with SC criteria, Shanghai has the highest savings–to–increased exposure ratio (0.10) among the three Asian cities, while the ratio in Beijing is 0.06 and in New Delhi is 0.04. With EC criteria, Shanghai still has the highest ratio

Table 5.7 Ratio between average energy savings and increase in PM2.5 exposure [kW m/mg] for each NV–use scenario

City	SC			EC		
	NVP	NVF	NVS	NVP	NVF	NVS
San Diego	0.49	1.63	0.70	0.55	1.88	0.61
Burbank	0.31	0.99	0.54	0.35	1.13	0.37
Fresno	0.33	0.88	0.57	0.39	1.11	0.39
Sacramento	0.53	1.88	0.84	0.65	2.03	0.68
Livermore	0.71	2.20	0.99	0.66	1.95	0.72
Antwerp	0.35	0.97	0.52	0.34	0.89	0.45
Krakow	0.32	0.81	0.39	0.28	0.67	0.32
Lisbon	0.58	1.73	0.91	0.63	1.92	0.91
London	0.31	0.83	0.40	0.29	0.73	0.37
Madrid	0.44	1.24	0.65	0.54	1.52	0.69
Paris	0.34	0.93	0.48	0.33	0.80	0.44
Prague	0.41	1.16	0.55	0.39	0.99	0.48
Skopje	0.24	0.66	0.19	0.29	0.70	0.19
Strasbourg	0.40	1.14	0.52	0.37	0.98	0.45
Beijing (NV10; NV35)	0.06	0.18	0.08 0.11	0.08	0.23	0.08 0.11
Shanghai (NV10; NV35)	0.10	0.21	0.09 0.15	0.14	0.32	0.13 0.19
New Delhi (NV10; NV35)	0.04	0.13	0.04 0.04	0.05	0.16	0.04 0.04

(0.14), while in Beijing and New Delhi, the ratio increases to 0.08 and 0.05, respectively. As can be seen, the ratios increase for all three Asian cities, showing that the combined use of NV and PCS leads to an increase in energy savings that is higher than the increase in indoor exposure. Nonetheless, these ratios are up to one order of magnitude lower than the ranges found for the European and Californian cities. This large difference is mostly due to the significantly higher increases in PM2.5 exposure that occur in these three cities. Further, in all three Asian cities, energy savings are lower than elsewhere, mostly due to the lower availability of NV. In California and Europe, air pollution regulations are stricter and have been in place for a longer period, effectively improving air quality. In China and India, those regulations are more recent and less stringent.

Although limiting the increased exposure, the NV10 scenario does not allow for significant energy savings, resulting in a $\Delta e/\Delta P$ ratio similar to NVP in Beijing and lower in Shanghai and New Delhi. By increasing the outdoor PM2.5 concentration threshold (NV35), indoor exposure also increases, but so do energy savings. In all three cities, energy savings have a higher relative increase, hence the higher $\Delta e/\Delta P$ ratios. However, in New Delhi, this ratio is still lower than that found for the NVP scenario. Finally, as with both other analyzed regions, the best savings–to–increased exposure ratios occur with the NVF scenario.

5.4 Conclusions

Awareness on the negative health impact of airborne fine particle pollution is continuously increasing. Most airborne PM2.5 found in the urban environment can be traced back to man–made combustion from transport, industry, power generation and domestic fuel burning. Within the built environment, fine particles can be brought in from the outdoor environment, through infiltration or through natural or mechanical ventilation. In addition, PM2.5 can also be generated indoors, such as through the use of fuel for cooking and heating, or the occupant movement–induced re–suspension of particles that have previously settled onto surfaces. Natural ventilation typically does not provide any barrier to outdoor PM2.5, while in the case of mechanical ventilation, filters with a wide range of particle retention rates can be used. However, high filtration efficiency comes at the cost of a higher pressure load on the fan and, therefore, at the cost of a higher energy consumption.

The detailed thermal simulations presented in this chapter showed that using ventilative cooling whenever it can provide a cooling effect decreased the HVAC energy consumption (NVP), in comparison to a scenario with full–working time HVAC operation (NoNV) by 26–83% in California, 20–58% in Europe and 7–21% in Asia. The availability of PCS alone did not significantly decrease and, in some locations, even slightly increased the HVAC load. Nonetheless, these devices allowed an increase in NV use, which in turn increased its energy saving potential to 46–93% in California, 44–77% in Europe and 16–41% in Asia. Expectedly, this increase is highest in cities with the highest increase in NV availability due to the extended NV temperature range, namely Fresno, Sacramento, Lisbon, Madrid, Skopje, Beijing, Shanghai and New Delhi.

In comparison with a standard full–time HVAC operation scenario, using NV significantly increases indoor occupant exposure to fine particles. This increase is 3.7–5.0 times in California, 1.9 to 4.2 times in Europe and 2.3–3.0 times in Asia. PCS extend the use of NV and, thus, further the increase in exposure: 4.4–5.7 times in California, 2.2–5.4 times in Europe and 3.3 to 3.9 times in Asia.

With the goal of quantifying the trade–off between energy savings and increased exposure, the ratio between the yearly energy savings and the increase in cumulative PM2.5 exposure was calculated for the different cities. The locations with the lowest increased indoor pollution levels for the same energy savings favor NV use. Among the analyzed cities, this ratio is highest in Livermore and lowest in New Delhi. On average, the energy savings–to–increased PM2.5 exposure ($\Delta e/\Delta P$) is highest in California, due to the typically high NV availability and lower PM2.5 levels, and lowest in Asia, by up to an order or magnitude, where local climate does not favor extensive NV use and where PM2.5 levels are exceptionally high. Europe is placed in a middle position, with $\Delta e/\Delta P$ ratios of the same order of magnitude though lower, on average, than in California, since the use of NV is more limited by local climate and PM2.5 concentrations are higher than those typically found in that U.S. state.

Two approaches were followed to limit the increase in exposure that occurs due to the higher use of NV: limiting its use to when outdoor PM2.5 levels are low (NVS, with different thresholds for each region: 12 $\mu g/m^3$ in California, 10 $\mu g/m^3$ in Europe and both 10 and 35 $\mu g/m^3$ in Asia) and using an electrostatic filter to reduce particle penetration (NVF).

Understandably, the reduction in NV use due to its limited availability to moments with low outdoor PM2.5 also reduces NV's energy saving potential: 17–63% in California, 5–40% in Europe and both 1–5% (with a threshold of 10 $\mu g/m^3$) and 1–12% (with 35 $\mu g/m^3$) in Asia. When PCS are available, the energy saving potential is also diminished: 38–86% in California, 12 to 63% in Europe and both 4–22 and 4–35% (thresholds of 10 and 35 $\mu g/m^3$, respectively) in Asia. Nevertheless, this exposure control approach achieves its goal of decreasing occupant exposure to PM2.5. In California, occupant exposure is between 2.0 and 3.2 times the exposure that results from the full–time use of HVAC, while in Europe, occupant exposure is between 1.4 and 2.8 times the NoNV levels. In Asia, both thresholds place a strict restraint on the use of NV, limiting occupant exposure to between 1.2 and 1.8 times the NoNV levels. The higher use of NV that results from the use of PCS also increases occupant exposure, even in this exposure control approach: 3.7–4.9 times the NoNV exposure in California, 1.7–3.3 times in Europe and 1.9–2.6 in Asia. With few exceptions, namely Skopje, Shanghai (in the case of the 10 $\mu g/m^3$ threshold) and New Delhi (for both the 10 and 35 $\mu g/m^3$ thresholds), the $\Delta e/\Delta P$ ratio is higher when NV is limited to moments of low outdoor PM2.5, since most energy savings occur during moments with low outdoor particle levels.

The use of electrostatic façade NV inflow filters seems to achieve the best of both worlds. These filters have a very low energy cost which, combined with the possibility of using NV whenever it can provide a cooling effect, result in energy savings that are nearly identical to those found in the NVP scenario. At the same time, these filters allow occupant exposure levels that are, in most cases, similar to or lower than those associated with the NVS approach. As a result, the energy savings–to–increased PM2.5 exposure ratio is highest for this scenario.

Overall, NV has an energy–saving potential of up to 83%, with standard NV criteria, or 93%, in the case of available PCS, which extend the NV–favorable temperature range. However, NV is not a solution that can easily be used in any location, since some climates nearly eliminate any possible NV use, even with an extended NV temperature range. Further, the unrestricted use of NV can increase indoor exposure to fine particles of outdoor origin by up to five–fold (or sixfold, if used in combination with PCS) in comparison with an office using an HVAC system in full–time operation with a high–efficiency fine particle filter.

Two approaches can be used to limit this increase in exposure to 2–3 times. Using NV only when outdoor PM2.5 concentrations are low is a solution that could be implemented with ease in existing commercial buildings. In this case, the energy–saving potential of NV is reduced to 63% (86% if used in combination with PCS), although this reduction is lower than the reduction in cumulative exposure. Using NV with openings equipped with an electrostatic filter can also decrease indoor PM2.5 levels and at a very low energy cost, thus, taking advantage of nearly all of NV's energy saving potential. However, any attempt to apply this approach in an existing building has not been found.

Still, limiting man–made combustion, namely by decreasing traffic or shifting to cleaner energy sources is the most efficient path for decreasing outdoor PM2.5. The use of cleaner energy sources indoors also decreases PM2.5 levels within the built environment, as does the use of effective extraction ventilation for indoor sources. The proposed innovative solutions limit the penetration of outdoor PM2.5 through the incoming airflow and can also be part of the solution to decrease exposure to PM2.5. Ultimately, one of the most important steps is to increase public awareness of PM2.5, encouraging people and national governments, on their behalf, to engage in these solutions as well as developing other solutions.

Annex I: Parameter Sources

See Table 5.8.

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Table 5.8 Parameter sources

Parameter		Refs.	Value
Base model	Constructions	[197]	–
Perimeter zones	Zone depth		6.096 m
Internal mass	Furniture	[205]	2×0.10 cm/m^2
Windows	Construction	[203]	–
	Thermal properties	[204]	1.333 W m^{-2} K^{-1}, U–value; 0.283, SHGC

(continued)

Table 5.8 (continued)

Parameter		Refs.	Value
Restrooms	Number	[199]	3, per gender
	Dimensions	[200]	–
Vertical access	Elevator	[200]	–
	Stairs	[201]	–
Corridor	Dimensions	[201]	–
Air tightness	Infiltration rate	[206]	0.00136 $m^3\ s^{-1}\ m^{-2}$ (of external area); ×0.25 when HVAC is on
Lighting	Load		8.07 W/m^2, offices; 6.46 W/m^2, remaining zones; ×0.25, unoccupied period
	Schedule	[136]	–
Equipment	Load and schedule	[136]	9.74 W/m^2; ×0.33, computers, unoccupied period; ×0.20, monitors, unoccupied period
Occupation	Density	[208]	11.6 m^2/workspace
	Schedule	[207]	–
Mechanical ventilation	Ventilation rate		8.50 $m^3\ h^{-1}$ $person^{-1}$, office; 1.10 $m^3\ h^{-1}\ m^{-2}$, office and corridor
	Pressure load	[210]	1438 Pa
	Fan efficiency	[210]	50.1%
Air handling unit	Heat pump efficiency	[209]	40%
	Heat recovery efficiency	[211]	80%
Heating & cooling	Set points	[29]	20 °C, heating; 26 °C, cooling; SC
		[34]	18 °C, heating; EC
		[31]	30 °C, cooling; EC
	Heated chair power	[34]	16 W/chair
	Fan	[31]	1.6 m/s; 1 fan/workspace
Natural ventilation	Opening area	[214]	1–3.5% of floor area
	Single–Sided ventilation modeling	[213]	–

(continued)

Table 5.8 (continued)

Parameter		Refs.	Value
Contaminant modeling	Deposition rate	[108]	0.19 h^{-1}
	Infiltration particle penetration rate	[108]	80%
	Re–suspension	[96]	59.8 $\mu g/cm^2$, floor load; 4.4×10^{-7} h^{-1}, rate
Cloth fine particle filter	Efficiency	[25, 216, 217]	71.4%
Electrostatic filter	Efficiency	[167]	63%
	Power consumption	[167]	0.73 W s/μg (27.5 kV; 26.5 μA s/μg)

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Chapter 6
Ventilative Cooling and Control Systems

Hilde Breesch and Bart Merema

Abstract Robust control systems are essential to guarantee an efficient usage of ventilative cooling. The most important challenges of controlling natural ventilative cooling are the outdoor environmental conditions like wind, rain, noise and pollen; security and interaction with and satisfaction of the user. The main control strategies and components of natural ventilative cooling, including actuators and sensors are described. From case studies, the following lessons are learned. The main driver for control of natural ventilative cooling systems is thermal comfort and outdoor weather conditions. Optimization and commissioning of ventilative cooling control is critical to maximize the cooling potential as well as to prevent overcooling. Conclusions on the interaction of the user with the ventilation cooling control are twofold. On the one hand, automatic control is preferred to manual control of ventilative cooling. On the other hand, the user should be able to overrule this automatic control. Suggestions for design are formulated. The users and their expectations of controllability play a central role. Moreover, the future maintenance of the actuators have to be taken into account in the design phase.

6.1 Introduction

Nearly Zero Energy Buildings (nZEB) not only consist of a highly insulated and an airtight building envelope but also have elaborated systems for sanitary hot water, heating, ventilation and cooling (HVAC). A Building Management System (BMS) managing the HVAC systems is essential in these nZEB buildings to maximize the indoor comfort while minimizing the energy use. Automatic control of ventilative cooling is one component of this BMS and is essential to guarantee an efficient and effective usage of ventilative cooling. The purpose of ventilative cooling control is to

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adapt the airflow rate to the actual cooling demand without compromising the thermal comfort and the indoor environmental quality. As a consequence, both ventilation and control system have to be integrated and designed in parallel.

This chapter describes the main control strategies and components, including actuators and sensors, with special regard to natural ventilative cooling. Case studies and practical applications are studied to define guidelines and suggestions to effectively control ventilative cooling systems in residential and non-residential buildings in different climates.

6.2 Control Strategies

6.2.1 Overview of Strategies

Manual control of ventilation openings has the advantage of its simplicity and low maintenance, but the disadvantage that it may not respond properly to complicated and dynamic external circumstances nor internal activities of occupants. As a consequence, spontaneous occupant control generally shows sub-optimal performance regarding energy savings and thermal comfort [1]. The following automated control strategies for window operation are proposed to better realize ventilative cooling potential in buildings. First is conventional rule-based heuristic control [2], second the more advanced model predictive control (MPC) [3, 4], and third newly developed control strategies that use machine-learning techniques [5].

Rule-based heuristic control is the most common control strategy for operable windows and HVAC systems. This strategy can be visualized in a decision tree, where each parameter is compared to threshold value (or criterion) causing a specific action or leading to another leaf node with another criterion comparison (see Fig. 6.1a). Rule-based heuristic control has a fairly low technical barrier when implemented in a real system hardware and an adequate performance is typically expected [6].

A model predictive control (MPC) strategy, as seen in Fig. 6.1b, optimizes the actions by simulating the system using a physical or empirical model on a finite time-horizon. MPC has already shown savings for hydronic systems in operating buildings as indicated in recent studies (e.g. [7–10]), but is not widely used in ventilation systems. Potential of MPC in ventilation is amongst others studied by [11–21]. A well-designed MPC has the advantage that it can outperform a rule-based heuristic control on both thermal comfort and energy savings. However, MPC is much more complicated and requires an accurate mathematical model of the building system for prediction and optimization [6].

Reinforcement learning methods have the advantage compared to MPC that they are able to find optimal actions without requiring a model of the building and its system. While treating the environment as a black box, the algorithm is able to learn from the interaction with the environment [6], as shown in Fig. 6.1c.

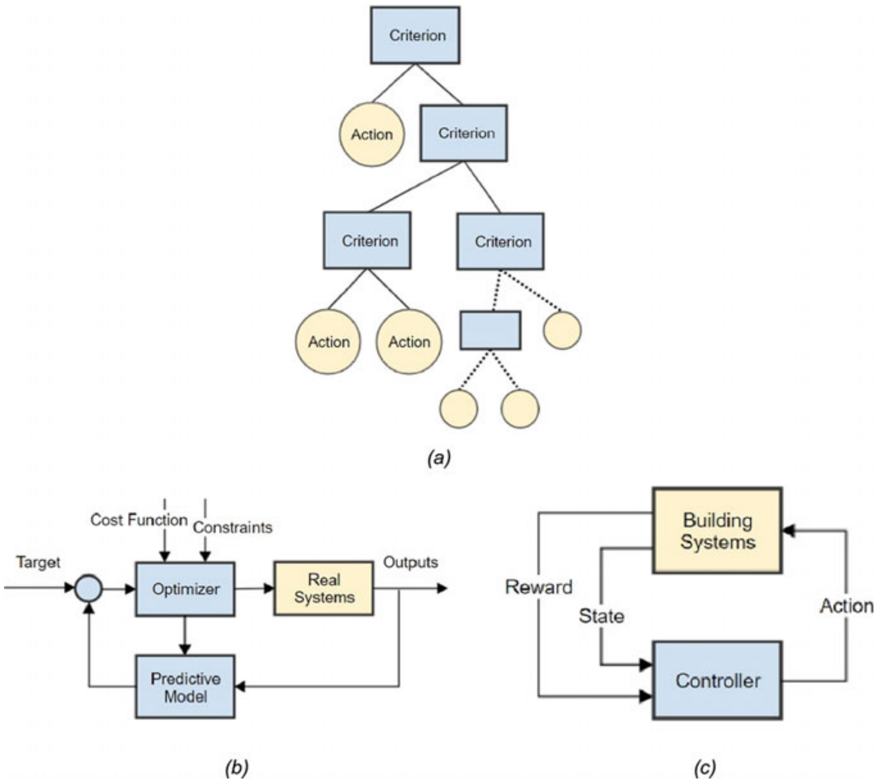

Fig. 6.1 Schematic representation of rule based control (**a**), model predictive control (**b**) and reinforced learning (**c**) [6]

6.2.2 Challenges

One of the main challenges of controlling natural ventilative cooling components are the outdoor environmental conditions. Rain and wind can limit the window opening. If adequate protection is not provided, window opening has to be restricted to avoid rain ingress or damage to the building [22]. As a consequence, rain and wind sensors are required to establish limitations on the opening control [23]. In addition, control systems need to be designed and controlled accordingly to avoid noise through ventilative cooling openings, e.g. at night or during rush hours (traffic noise). Moreover, during pollen season, occupants with allergies may not want the windows to be opened [23].

Another challenge of control is the security of open air inlets, especially when natural ventilation is used during unoccupied hours for nighttime ventilation. It is common to provide opening windows under occupant control in addition to the vents operated by the BMS system [22].

An next challenge is the interaction with and the behavior of the user. To have a high level of user's satisfaction and acceptability, users should get more information on how to modify or overrule the automatic ventilative cooling control. Although it is recommended that occupants should have the possibility of controlling their own environment, automatic control is necessary to support them in achieving a comfortable indoor climate and to take over when manual control cannot improve the condition and during non-occupied hours [23]. It is a challenge to find a balance between the satisfaction of the user and a good thermal comfort and maximum energy savings by automated control.

6.3 Control Components

Typical ventilative cooling components can be subdivided in air flow guiding; air flow enhancing; passive and natural cooling; and control and automation components [23]. The latter includes actuators and sensors.

An actuator responds to the output signal from a controller and provides the mechanical action to operate the final control device [22]. The core issue regarding actuation in ventilative cooling is modulating (opening and closing) the inlet and outlet air flow guiding components like windows and louvres.

Automated control includes sensors that measure internal and external environmental parameters e.g. indoor and outdoor temperature, to provide a feedback. Accurate sensors are a vital component of the control because computing or software functions cannot compensate inaccurate information for poor-quality of inappropriately mounted sensors [22].

6.3.1 Actuators

There is a large variety of actuators available: chain (including folding), linear and rotary actuators are the most commonly used for the operation of ventilation elements [24].

Chain actuators deliver a pushing steel chain and offer the benefit of slim construction without the disadvantage of the rod casement compromising the use of the adjacent space. They are commonly used for windows which are accessible by people, both top hung, side hung and also roof vent windows (see Fig. 6.2). In comparison to linear actuators, chain actuators offer the big advantage of small dimensions but are comparably limited in stroke and force [24].

Figure 6.3 shows an example of a linear and folding actuator. Linear actuators consist of solid tubes or prisms, with a push-rod, driven by an electric motor via a spindle or rack and are commonly used for domes, smoke exhaust flaps and for high

Fig. 6.2 Examples of chain actuators to open a window in Solstad Kindergarten in Norway (left) [25] and office buildings in Belgium (middle and right)

Fig. 6.3 Examples of linear [26] (left) and folding (right) actuators

level windows which are out of reach from persons [24]. Moreover, folding actuators and rotating arms are both suitable for top and bottom as well as side-hung windows and have opening angles even beyond 90° [24].

6.3.2 Sensors

To guarantee a robust automated control of the ventilative cooling system, sensors have to meet the following requirements [27]. It is important that the operating range of the sensors includes the expected range of the measuring values to avoid errors. In addition, the accuracy determines the precision of the measured data. Before installing the sensors, the level of accuracy needs to be determined. The claimed accuracy of a sensor may not be available over the whole operating range. The accuracy can be affected by the stability of the sensor, hysteresis or environmental variables [22]. As a consequence, a high stability is advised for a period of at least 5 years where no recalibration is needed. A correct and linear output signal with a minimal deviation and low hysteresis is also required. For operation and control of the ventilative cooling, the response time of the sensors is also of importance. With a fast response time the system can control more stable and accurate the actual demand inside the room [22]. Moreover, a high precision and reproducibility and lack of interference with other sensors is important. This is especially the case for wireless sensors [28]. Furthermore, the position of the installed sensors needs attention. A position in direct sunlight or close to a door, window or air supply must be avoided.

Typical internal environmental parameters that are used for ventilative cooling control are: room and/or slab temperature, relative humidity (especially in humid climates or rooms with large humidity production), CO_2-concentration or occupancy (especially in buildings with large but variable occupancy). In addition, external environmental parameters for ventilative cooling control include external air temperature, wind speed (to avoid damage or over-ventilation), wind direction (to select windward or leeward openings), rain intensity or precipitation (to avoid rain ingress through large ventilation openings).

For each parameter, different types of sensors are available. Table 6.1 summarizes the characteristics of the different types of sensors available for the most relevant parameters for ventilative cooling control. The listed sensors are well spread within building use to control heating, cooling or ventilation systems.

Three types of sensors are recommended to measure room temperature for ventilative cooling control. Thermistors and resistance temperature devices (RTD) deliver the highest accuracy but have a slower response time compared to a silicon temperature sensor. Silicon temperature sensors are found in most temperature sensors which are used in rooms to control the heating or ventilation system since they are easy to implement and are digital.

Table 6.1 Characteristics of sensor types for parameters for ventilative cooling control [22, 28–30]

Measured parameter	Type of sensor	Accuracy	Response time	Measuring range
Room temperature	Thermistor	±0.1–0.5 °C	10–30 s	−50–180 °C
	RTD	±0.15–0.6 °C	25–60 s	−50–100 °C
	Silicon temperature sensor	±0.50	1–60 s	−50–150 °C
Relative humidity	Capacitive polymer	±2–4.5%	10–50 s	0–100%
	Ceramic resistance	±2–5%	10–50 s	10–90%
CO_2 concentration	NDIR	±30–80 ppm	30–50 s	0–2000 ppm
Occupancy	PIR	3–5 m radius or 5–12 m front and 3–8 m lateral	10 s–15 min	
	Ultrasonic	185 m^2	30 s–30 min	

For measuring the relative humidity, a capacitive polymer or a ceramic resistance can be used. Both types of sensors have a comparable accuracy and response time. The main difference is the measuring range for both sensors [29].

CO_2-concentration inside buildings can be measured by nondispersive infrared (NDIR) sensors, which offer a good accuracy. Response time is usually around 30 s. Still these sensors are expensive compared to temperature and humidity sensors. For CO_2-concentration, it is recommended to have a sensor with an accuracy of ± 50 ppm in the range of 400–2000 ppm. Recalibration for the sensors is advised at least every 5 years.

For occupancy, two techniques can be used to detect if people are inside the room or not. The passive infrared (PIR) detects if persons are inside a predefined range of the sensor. If people are too far from the sensor no presence is detected. The ultrasonic sensor is more accurate, since they do not use a fixed field of vision [28]. This type of sensor is based on the Doppler effect.

6.4 Case Studies and Applications

This section analyses the strategies and components that are used to control ventilative cooling. In addition, the specific control strategy of 3 different case studies worldwide is discussed in detail.

6.4.1 Overview

To evaluate the most common measured parameters and components used for the ventilative cooling control strategy, data is collected from 115 case study buildings [31, 32]. Out of these 115 buildings, 25% are educational buildings, 46% office buildings, 11% residential and 18% other type of building use. For the collected dataset the most common type of ventilation strategy was hybrid ventilation with a total of 61%, automatic natural ventilation was used in 37% of the buildings and manual natural ventilation in 3% of the buildings.

For ventilative cooling, the used control strategy is of crucial importance and depending on the used ventilation strategy of the building. Figure 6.4 shows the parameters used for the ventilative cooling strategy in the collected dataset. The main driver is the thermal comfort of the user as the measurement data demonstrates. In 92% of the cases studied, the internal and external temperature sensors are used to control the ventilative cooling system. CO_2 and humidity sensors are also commonly used as control parameters for the ventilative cooling to maintain a comfortable indoor climate, in respectively 75 and 53% of the buildings. In addition, external weather conditions (wind velocity, precipitation) are used for natural or hybrid systems. For purely mechanical systems, the external weather conditions like precipitation or wind, are not considered.

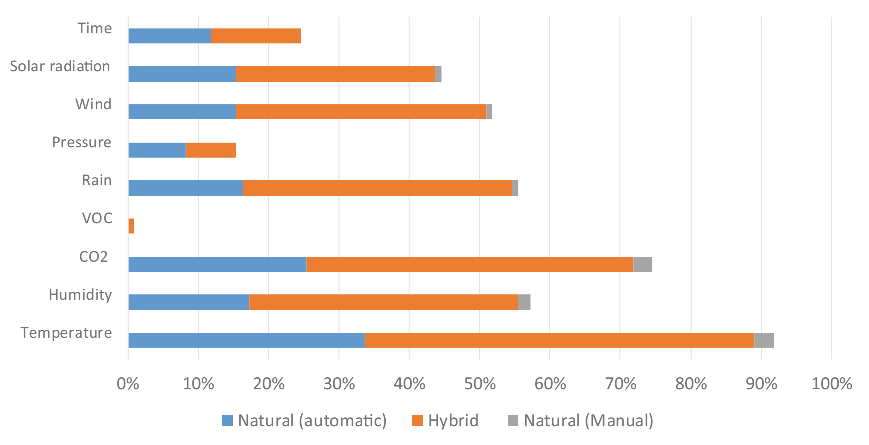

Fig. 6.4 Summary of sensors used in ventilative cooling control strategies [32]

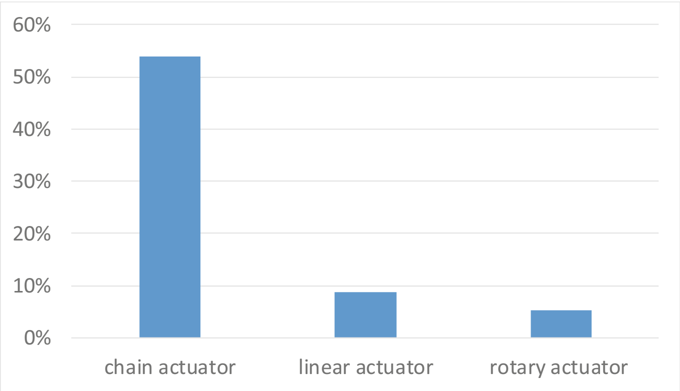

Fig. 6.5 Used actuators for ventilative cooling control strategies [32]

The most common type of actuator, used in the studied cases, is the chain actuator, as depicted in Fig. 6.5. In 54% of the evaluated buildings, this type of actuator is implemented for the window control. Two other types that are used are the linear and rotary actuator, in respectively 9 and 5% of the case studies.

6.4.2 *Test Lecture Buildings KU Leuven (Ghent, Belgium)*

In this educational building in Belgium, two control strategies can be defined as illustrated in Fig. 6.5. The first control is active during occupancy, the second control strategy is active at night for the control of the natural night ventilation. The first

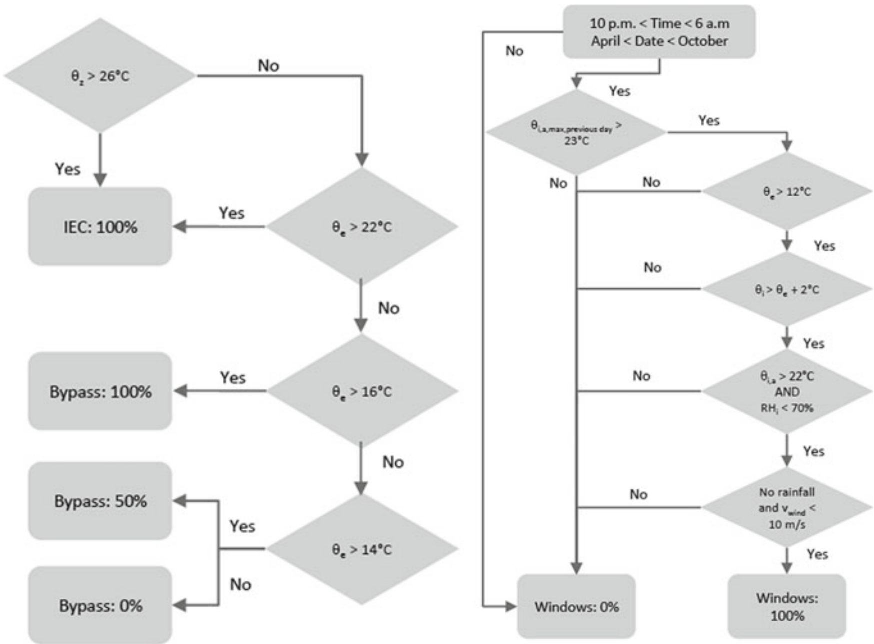

Fig. 6.6 (Left) Control strategy during occupancy, (Right) Control strategy natural night ventilation [33]

control strategy involves the mechanical ventilation system that is active during occupancy and is based on the internal and external temperature. The air handling unit (AHU) cools the supply air by controlling the bypass of the heat exchanger and by using indirect evaporative cooling (IEC) [33].

The second control strategy involves the actuation of the windows and is based on the internal temperature and external weather conditions. The night ventilation is based on predefined criteria based on indoor and outdoor conditions. When the criteria are fulfilled the night ventilation is activated between 22:00 and 06:00 h. When the night ventilation is activated the windows will be opened automatically on both sides of the classroom (Fig. 6.6).

6.4.3 Nexus Hayama (Japan)

In this office building in Japan [25] the control strategy is based on the actuation of the high-level automated openings. The natural ventilation is driven by temperature difference and wind and is used in spring (April to June), early summer and fall (October to November). The outside air is introduced from the top and first floor to the occupied zones of the building. The exhaust openings, using the principle of

Table 6.2 Conditions for operation of the natural ventilation openings [25]

Parameter	Condition
Enthalpy	Outdoor enthalpy < room enthalpy
Zone temperature	External temperature ≤ lowest zone temperature in atrium lounge
External temperature	15 °C ≤ external temperature
External dew point	External dewpoint ≤ 20 °C
External wind	Wind velocity <10 m/s
Rain	No rain
Others	AHU operate in cooling mode

an H-type chimney, are located on top of the building. For the considered control strategy, the following parameters are involved: enthalpy, zone temperature, external temperature, external dew point, wind speed and direction, rain. The ventilation opening is controlled automatically based on the aforementioned parameters and the defined zone conditions as depicted in Table 6.2. Regarding the room temperature control: when the room temperature exceeds 28 °C, the system automatically switches to temperature control and the air conditioning system is used.

6.4.4 *Brunla School (Norway)*

This school building in Norway [25] is operated by a mechanical ventilation systems combined with operable windows. The natural ventilation in the classrooms is single sided where each window can be opened individually. The control strategy is based on both the desired indoor air quality as the indoor temperature with priority for the thermal comfort. All the ventilation strategy modes are listed in Table 6.3 and are based on internal or external conditions. Opening of the windows is controlled automatically. In addition of the windows, the mechanical exhaust ventilation can be used if CO_2 levels are above the predefined set point. When the natural force is insufficient or when high loads are requested the variable speed fan can increase the pressure differences, since the outlet is connected to a duct with dampers and thus control the airflow rate.

An external weather station is installed on the roof of the building and the data collected is considered by the control system. The window opening is controlled and is based on the weather conditions and the internal temperature and CO_2. Users can override the window opening allowing to open and close the window when desired, however after 15 min the control system regains the control and acts accordingly to reduce the energy use.

Table 6.3 Ventilation control strategy modes [25]

Parameter	Ventilation modus
Fresh air, standby when $T_{outdoor} > 20$ °C	Natural ventilation
Comfort ventilation 12 < $T_{outdoor} < 20$ °C	Hybrid or natural ventilation
Just manual control, Any time the system can be overruled	Manual control
Closed windows, Comfort $T_{outdoor} < 12$ °C	Exhaust ventilation
Closed windows, night $T_{outdoor}$ < 12 °C	Exhaust ventilation
Night ventilation $T_{in} > 20$ °C	Hybrid or natural ventilation
Pulse ventilation $T_{outdoor}$ < 12 °C	Hybrid or natural ventilation
Slot ventilation $T_{outdoor} < 12$ °C	Hybrid or natural ventilation

6.5 Lessons Learnt And Suggestions For Design

Each case study in the "Ventilative Cooling case studies" [25] of IEA EBC Annex 62 contains a section "Lessons learnt". Conclusions regarding control are summarized and structured into the following topics: commissioning and optimization; user interaction and control; and suggestions for design.

6.5.1 Commissioning and Optimization

Optimization and commissioning of all the systems, including ventilative cooling, in each season are critical to maximize the cooling potential as well as to prevent overcooling. Two aspects can be distinguished in the lessons learnt from the case studies of IEA EBC Annex 62 [25].

First, amongst others, case studies in Norway, Ireland, Austria and Belgium show that the control system has to be trained, fine-tuned, adapted and optimized on a regular basis. It can take considerable time to establish an effective strategy with variable values and parameter settings. Preferably, more than one cooling and heating season is used to optimize the systems.

Second, a data monitoring system is essential to detect malfunctions in the control system and to optimize the interaction of different technical building and control systems. This was shown in an educational building in Belgium and an office building in Austria [25]. However, the Irish case study showed that monitoring is only justified if there is budget to maintain the system as well as to analyze the collected monitoring data [25].

6.5.2 User Interaction

Different cases show different opinions on the interaction of the user with the ventilation cooling control.

On the one hand, automatic control is preferred to manual control of ventilative cooling. Psomas et al. [34] proved in a residential building in Denmark that during mild summer conditions automated windows may significantly decrease thermal discomfort and overheating risk compared to manually opening of the windows. The effectiveness of occupant manually operated windows or louvres to control ventilative cooling reduces over time. This is shown in the offices in the zero2020 building in Ireland [25]. Occupants take less responsibility for maintaining the indoor thermal comfort. Moreover, manual control is unsuitable in high-rise buildings as experienced in Japan [25].

On the other hand, dwellings in France and China showed that it is really important that the user can overrule the automatic control of ventilative cooling [25]. Also in a Norwegian school, users are satisfied that they are able to control the ventilative cooling system [25]. A hybrid system, i.e. an automated control that indicates to the user when to manually open and close the windows, was tested in the Italian dwelling [25]. The occupants were in general satisfied with the suggestions of the BMS but indicated that manually opening and closing of the windows can become burdensome and is consequently not advised.

It can be concluded that an automated control with the possibility to ignore or overrule this control is the best option for a reliable system with a maximum cooling efficiency as well as a maximum user satisfaction.

6.5.3 Design Suggestions for Control

In the design of the ventilative cooling control, the users and their expectations of controllability play a central role. The Austrian office building noted that "the future building operator should be already involved in the planning phase to receive know how regarding the technical building systems features. He/she is the key actor for handling the technical building systems and building optimization." [25] In the apartment building in Japan, it was shown that it is important that the openings can be controlled for each individual tenant to meet their own needs [25]. Controls have also been designed to give flexibility to the occupants as experienced in a computer room in the UK [25].

Another aspect that is important to take into account in the design phase is the future maintenance of the actuators. The users of an office building in Belgium [25] advised to make the location of the actuators (here placed in the extraction stacks) easy accessible for maintenance and replacement. In addition, the Italian case study showed that harmonization of different communication protocols is rather complex and have to be taken into account the design phase [25]. Moreover, the Norwegian case studies underline the importance to have accurate and well calibrated sensors for the control of ventilative cooling.

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Part II
Techniques

Chapter 7
Ventilative Cooling in Combination with Passive Cooling: Thermal Masses and Phase-Change Materials (PCM)

Maria Kolokotroni and Thiago Santos

Abstract This chapter first describes the relation between the potential of ventilative cooling to reduce building cooling loads and the role of thermal storage to achieve this; thermal storage could be sensible in the form of exposed thermal mass embedded in the structure of the building or latent in the form of phase change materials embedded in the structure or decoupled from the structure but coupled with the ventilation system. The principles of how thermal storage contributes to passive cooling are described with examples from materialised case-studies. The chapter includes results related to the use of phase change materials in combination with ventilative cooling from an operational system.

7.1 Introduction

One design strategy to increase the performance of ventilative cooling is the incorporation of thermal mass in the building elements or in dedicated thermal storage systems. Thermal mass needs to be coupled with the ventilating air so that increased cooling can be achieved.

Coupling ventilation with thermal mass in buildings to provide cooling is not new; it has been traditionally used in many vernacular buildings mainly in hot and dry climates. Wikipedia [1] defines vernacular architecture as 'architecture characterised by the use of local materials and knowledge, usually without the supervision of professional architects. Vernacular buildings are typically simple and practical, whether residential houses or built for other purposes'. Climatic conditions alongside culture and local materials are the main parameters influencing the construction of these buildings.

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With the revival of bioclimatic design in the last 40 years to reduce energy demand in buildings, vernacular methods have been translated to principles of passive design suitable for modern buildings. In terms of thermal mass, what is new is the increasing availability of design guidelines, calculation methods in coupling thermal mass with ventilation and incorporation of new materials such as phase change materials (PCM) in the design of buildings.

Annex 62 state-of-the-art-review on ventilative cooling completed in 2015 [2, 3] revealed that some common components were used in the 26 operational buildings revisited as part of the review, built after 2000 and located in a variety of climatic conditions. These include *thermal mass*, grills, fans, CO_2 and temperature sensors, manually operated and/or motorised windows or special ventilation openings, and wind towers, solar chimneys or atria for exhaust. The review also revealed that many of the buildings make use of night ventilation to reduce the cooling load and avoid overheating of both new and renovated buildings. However, energy performance regulations in many countries do not fully integrate the parameter of thermal mass in calculations.

In this chapter the relation between the potential of ventilative cooling to reduce building cooling loads and the activation of building thermal masses is studied and presented in three main sections.

Section 7.2 presents the main principles of ventilative cooling and thermal storage, starting with an outline of night ventilation cooling and sensible thermal storage (surface and core activation). It continues with latent thermal storage, phase change materials and encapsulation for application to building surfaces or decoupled from the building envelope and gives an example of the operation of a ventilation system incorporating latent thermal storage.

Section 3 presents case-studies and results from the Annex 62 case-studies incorporating thermal mass with emphasis on the latent thermal storage case-study.

Section 4 outlines cooling potential calculation approaches incorporating thermal mass as used in the study of the case studies presented. It presents results on the estimation of night cooling potential for a variety of climatic conditions.

7.2 VC and Thermal Storage: Main Principles

Combining ventilative cooling with thermal mass requires charging and discharging of the thermal mass materials sensible or latently; this is explained in the following sections of this section.

7.2.1 Night Ventilation

Charging and discharging the thermal mass requires suitable ambient conditions to be used at specific times. In many climates and buildings types this can be done during the night using natural or mechanical ventilation to cool the thermal mass at night so that they can absorb heat during the day, thus requiring less energy for conditioning the air. This strategy has been termed ‘night cooling’ sometimes also called ‘night purging’. Currently, it is used almost routinely by building designers as its effectiveness has been proved in practice and has been promoted in many countries during the last 20–30 years. An example of such promotion in the UK more than 20 years ago [4] is shown in Fig. 7.1; it shows that night ventilation reduces air and surface temperatures, and delays the peak internal temperature to later in the day. It is encouraged as a default low energy strategy by building regulations and guidelines in many countries. For example, in the EU the Energy Performance in Buildings Directive recast [5] refers specifically to building overheating issues (article 25) and names ‘sufficient thermal capacity’ and the application of ‘passive cooling techniques’. EN 16,798–2019 [6] gives a separate method of calculating thermal comfort based on adaptive principles for buildings without mechanical cooling which rely on passive methods to reduce high indoor temperature during the warm season. Another example is its inclusion in many Green Rating schemes for providing points such as BREEAM (night-time cooling which requires fabric to have a high thermal mass).

A state-of the art review of passive cooling technologies is provided by Santamouris and Kolokotsa [7], which among other technologies includes description of

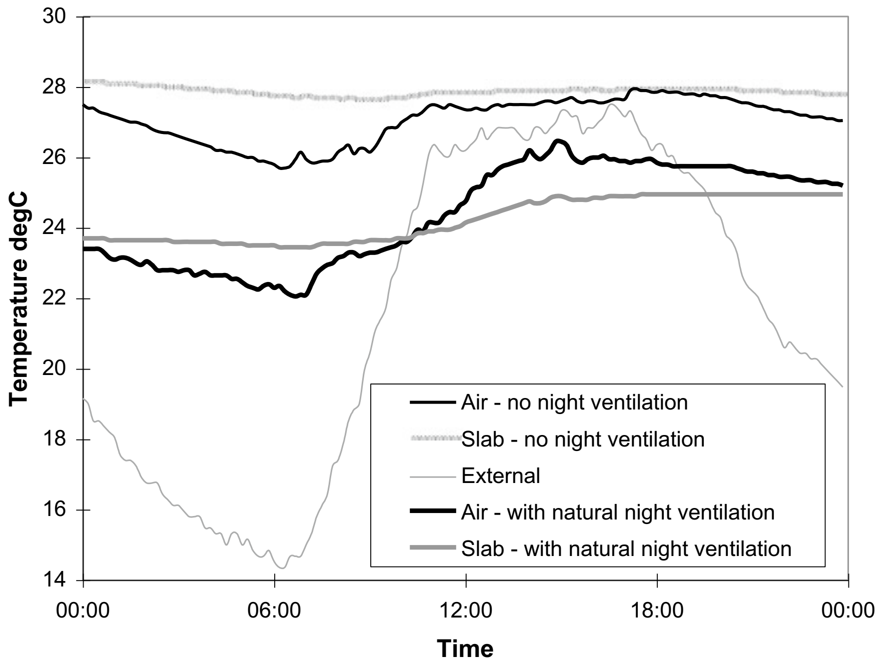

Fig. 7.1 Measured air and surface slab temperature variations over 24 h in an open plan office with and without natural night ventilation (Reproduced from [4])

recent studies related to design and operation of night-time ventilative cooling. They present published results of energy savings and improvement of thermal comfort in several buildings. In naturally ventilated offices an improvement of 1.5–2 °C is achieved in temperate climates while air conditioning savings of 5% and up to 40% for optimised offices can be achieved. In northern China internal surface temperature can be reduced by 3.9 °C. In warm climates peak cooling demand reduction of 13% can be achieved. For residential buildings, in tropical climates (Malaysia) it was reported that night ventilation reduces the peak indoor air temperature by 2.5 °C and nocturnal air temperature by 2.0 °C on average. A study in Greece reported decrease of cooling load up to 40 kWh/m^2/y with an average contribution close to 12 kWh/m^2/y. Other building types can also benefit; for example, in supermarkets compared with the normal active cooling system, the coupled operation system can save energy at 3 kWh/m^2/y in cold climates in China. A more recent similar study in the UK for supermarkets with high refrigeration load reports that night cooling optimally applied can lead to 3.6% reduction in the total energy use which equals to 40.8 kWh/m^2/y and reduction up to 17% in cooling demand and fans [8].

More recenlty, a review paper on night cooling was published [9] which presented a number of studies around the world and discussed the effectiveness and limitiations. The parameters that influence night cooling performance were classified into three broad groups:

- The *climatic parameters* such as local outdoor temperatures, daily temperature amplitudes, and topography.
- The *building parameters* such as the useful thermal mass available, the solar and internal heat gains, the presence of insulation, level of air tightness and functionality.
- The *technical parameters* such as the heat transfer coefficient, the optimal operation of the adopted cooling technique, the operational time and duration, air flow rates, and the night ventilation control algorithms.

One of the important parameters without which night ventilation can be compromised even if climate is favourable or the controls are present, is the availability of thermal mass so that cooling is well absorbed and correctly released during the day. Thermal mass can be embedded in the building envelope or decoupled using sensible and/or latent thermal storage. The following sections describe how these materials enhance the efficiency of ventilative cooling by utilising them during the night.

7.2.2 VC and Sensible Thermal Storage

In sensible thermal storage, the energy is stored by the temperature rise of a solid or liquid without phase change. Thermal storage embedded in the building structure (such as walls and ceiling) also sometimes called 'building heat capacity' or 'building thermal weight' refers to the amount of heat required to elevate the temperature of a unit mass of the material by one degree. In other words, the amount of heat energy required depends on the specific heat capacity of the material, temperature change and the amount of material. It is defined by:

$$Q = \int_{T_i}^{T_f} mC_p dT \tag{7.1}$$

where Q is the required heat energy in J, m is the mass of the material in kg, C_p is the material specific heat in J/kg K and dT is the temperature change in K.

Equation 7.1 implies that materials with high specific heat are better sensible thermal storage choices because they would require (absorb) more heat energy for the same temperature change. It also implies that we need as much material as possible. However, in a building's structure we have limitations on the amount of material we can include. Therefore, materials with high specific heat become important.

Thermal mass can also be incorporated in the building's structure or in areas not exposed to the conditioned air and be 'activated' using a fluid medium. Thermal mass activation components can be classified into two main categories [10], accordingly to the "activation principles", shown diagrammatically in Fig. 7.2.

Surface Thermal Mass Activation.

In this strategy the thermal mass is embedded in the internal surfaces of the buildings such as walls and ceilings. The cool air is circulated inside the building zones and heat is transferred in the exposed opaque elements of the building. The reduced temperature mass of the building contributes to reduce the indoor temperature of the next day through convective and radiative procedures. In direct systems, the mass of the building has to be exposed and the use of coverings or false floors or ceilings has to be avoided. In many cases we express the heat capacity or thermal mass of a buildings in the unit of area rather than in the unit of mass as we refer to building surfaces, therefore the unit of heat capacity is kJ/m^{2}K. This definition of heat capacity is used in most compliance tools, also called areal heat capacity. Therefore, the heat capacity of a building in the unit of area is the sum of the products of density, the

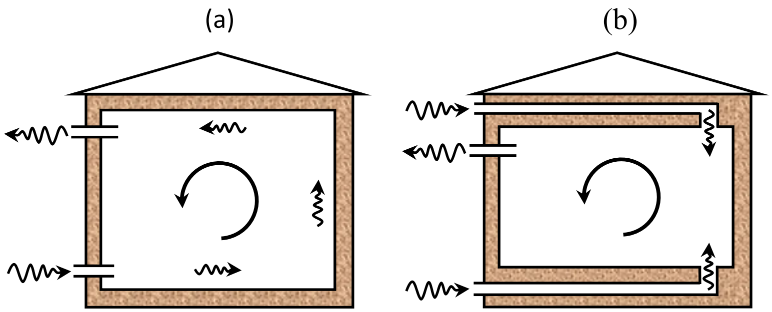

Fig. 7.2 Thermal mass activation working principles: **a** surface and **b** core

specific heat and the thickness of the building element. In this context, materials with high density are desirable as the thickness of building elements is restricted for cost reasons.

Heat transfer between the building material and air will depend on their areas of contact and therefore the ‘exposed’ to air area of the material should be as big as possible. For seasonal heat storage this is not very important but for daily storage and release of energy as in the case of night cooling the surface ‘heat capacity’ becomes important. In order to calculate the impact of ‘thermal mass’ the parameter of ‘admittance’ is introduced. This has the same unit as ‘heat transmittance’ or U-value but it describes the ‘rate of flow of heat between the internal surface of the structure and the environmental temperature of the space, for each degree of deviation of the space temperature about its means value’ [11]. Each of these parameters is expressed as an amplitude and an associated ‘time lead/lag’. Therefore, it enables us to calculate the rate of heat absorbed or released by the material or released over time. CIBSE Guide A explains in Sect. 3.8 that ‘for thin structure composed of a single layer the admittance is equal in amplitude to the U-value and has a time lead of 0. The amplitude tends towards a limiting value for thickness greater than about 100 mm. For multi-layers’ structures, the admittance is primarily determined by the characteristic of the materials in the layers nearest to the internal surface. For example, the admittance of a structure comprising heavyweight concrete lined internally with insulation will be close to the value of the insulation alone. However, placing the insulation within the construction, or on the outside surface will have little or no effect on the admittance’. In general materials with high density and heat capacity will have high admittance and therefore could be considered as high thermal mass materials if exposed to the internal space air. In most buildings concrete, brick and stone are considered good exposed thermal mass materials. Figure 7.3 shows effectiveness of thermal mass in reducing peak internal temperature depending on night ventilation rate and exposed thermal mass of the building for a case study library in the UK [12].

Core Thermal Mass Activation.

In such systems, the thermal mass is “equipped” with ducts for circulation of air or embedded pipes for circulation of a heat carrier (usually water). In these indirect systems, the cool air is circulated during the night, through a thermal storage medium where heat is stored and recovered during the day period. In general, the storage medium is a slab covered by a false ceiling or floor while the circulation of the air is always forced. Such systems can take the following forms:

1. Active Hollow Core Slabs: Hollow core pre-cast concrete slabs are used as a path for supply air thus increasing the coupling between the thermal mass and the supply air attenuating variations in ambient air temperatures as shown diagrammatically in Fig. 7.4.
2. Floor Void with Thermal Mass: A void created between a raised floor and a structural concrete slab as a supply air plenum, again increasing the coupling with the thermal mass and supply air.

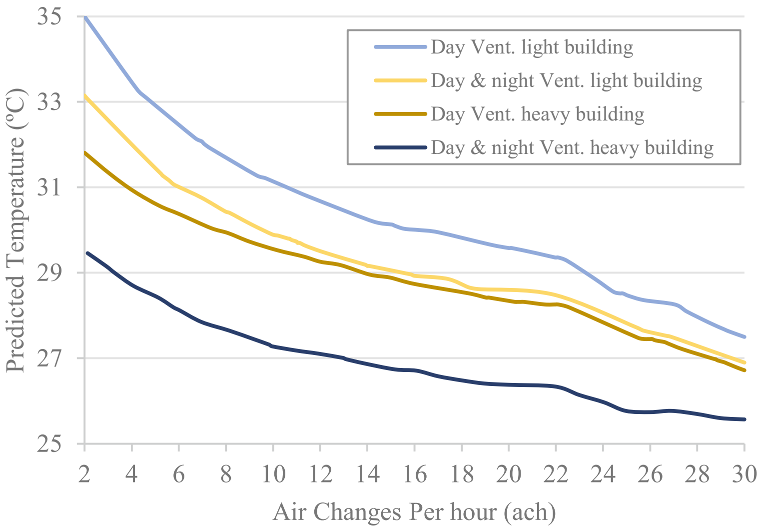

Fig. 7.3 Thermal mass effectiveness in a library building in the UK; (light building < 100 kJ/m^{2}K, heavy building >450 kJ/m^{2}K

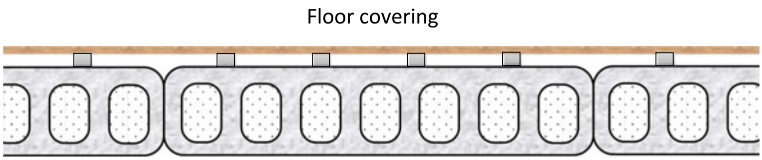

Fig. 7.4 Principle of a hollow deck with cavities for air circulation

3. Thermal Labyrinth: A thermal labyrinth decouples the thermal mass from the occupied space by creating a concrete undercroft, increasing the surface area of thermal mass, beneath the building. The benefits of decoupling the mass are that it can be cooled lower than if it was in the occupied space and the stored 'coolth' can be used to condition the occupied period for up to 3 or 4 days in hot periods.

7.2.3 VC and Latent Thermal Storage

Sensible thermal storage utilizes the heat capacity properties of materials while latent thermal storage uses heat exchanges via the phase change of materials, usually between solid and liquid for building applications. Latent thermal energy storage (LTES) can provide more energy per volume than a sensible thermal storage system, making LTES a promising solution for buildings either integrated into building envelope (passive LTES) or in ventilation systems (active LTES) to reduce cooling demand. This strategy employs latent heat to store energy which, typically, is charged (and solidified) during the night and discharged for cooling during the day by passing air across the Phase Change Material (PCM). Figure 7.5 shows diagrammatically the energy absorbed and released by the material. Phase change materials can be added into the building envelope or could be decoupled and be part of a heat exchanger in a ventilation system.

PCMs in the Building Envelope.

When liquid–solid or eutectic materials are added, an encapsulation is recommended if the material is added to the concrete mixture. Another option is to use solid–solid PCMs. Eutectic materials have a high volumetric thermal storage density, single melting temperature and the advantage to freeze and melt uniformly. However, few thermophysical property data are available and some fatty acids have a very strong odour which makes undesirable to be incorporated into the walls. When solid–liquid phase change materials are considered, PCMs can be encapsulated in materials such as plastic bags or aluminium pouches. The operation of this system is similar to the sensible thermal storage strategy as shown diagrammatically in Fig. 7.2.

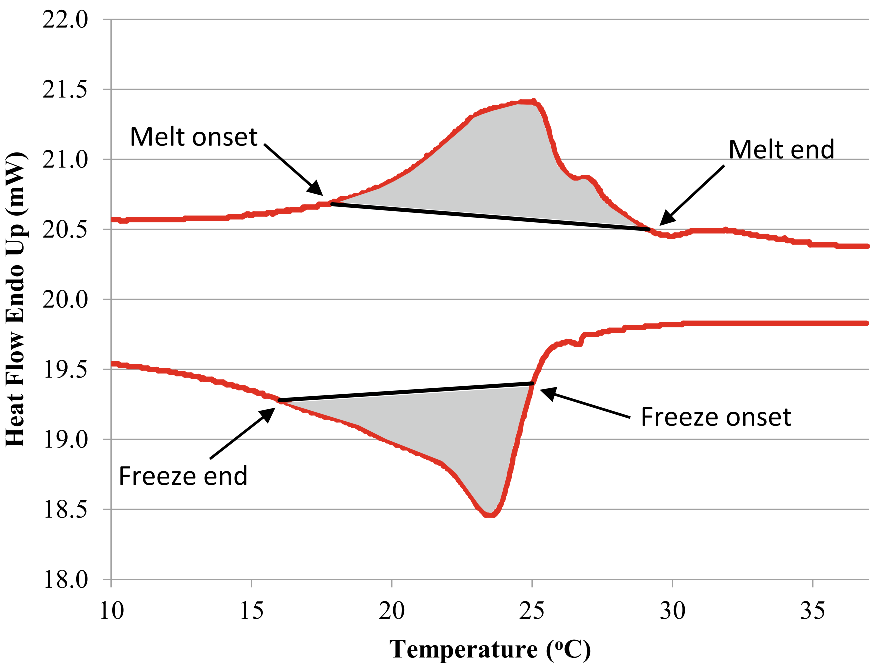

Fig. 7.5 PCM and capturing/releasing energy

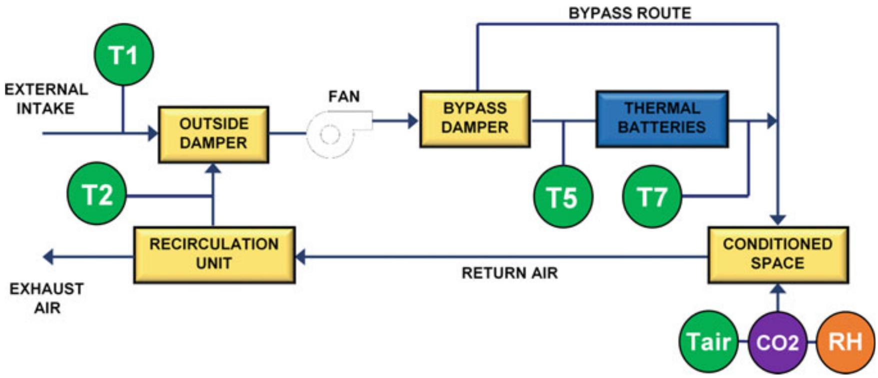

Fig. 7.6 Diagram of a mechanical ventilation system with PCM thermal storage. T1-T7, Tair, CO_2 and RH are sensors feeding to the control

PCM Decoupled from Building Envelope.

The use of active LTES integrated into a mechanical ventilation system (PCM-Air heat exchangers) received attention during the last two decades. A diagram of such a system is shown in Fig. 7.6.

Materials and Encapsulation.

PCM-air heat exchangers use the principle of thermal storage through latent heat in areas where night temperatures are cold enough to charge (solidify) the PCM and use it to cool the environment during the day. However, it performs better in places where diurnal temperatures range is higher than 15 °C [13]. Different materials can be used for the latent thermal storage. These may be classified into 3 main categories; organic, inorganic and eutectic materials [14].

- Organic Phase Change Materials can melt and freeze repeatedly without phase segregation, which would otherwise entail degradation of their latent heat of fusion. They can be further divided into paraffin and non-paraffin. Parrafins (usually straight chain n-alkanes), are safe, reliable, predictable, inexpensive and non-corrosive, however they have low thermal conductivity, are non-compatible with plastic containment strategies and are moderately flammable. Non-paraffins are the most numerous type of PCM and have a wide range of applications. Their characteristics include a comparatively high heat of fusion, inflammability, low thermal conductivity, varying level of toxicity, mildly corrosive as well as unstable at high temperatures. However, their most notable drawback, is their cost, which can be around 2 to 2.5 times greater than that of technical grade paraffins (Sharma 2009).
- Inorganic Phase Change Materials may be divided into salt hydrates and metallics. These phase change materials do not supercool significantly and their heats of fusion do not deteriorate with freeze and melt cycles. Salt hydrates are the most important variety of PCM, with extensive quantities of research concerning their

use in latent heat thermal energy storage systems. The most useful features of salt hydrates are their relatively high thermal conductivity, high latent heat of fusion per unit volume, and small volume changes upon melting. They are not very corrosive, compatible with plastic materials and possess low toxicity. The issues faced when using salt hydrates include incongruent melting which causes an irreversible phase change that gradually decreases with every cycle (Sharma, 2009). In addition, supercooling can interfere with effective heat exchange and in some cases prevent it entirely. Metallics include low temperature melting metals, which have not been considered as actively for PCM applications due to their undesirable weight disadvantages.
- Eutectic Phase Change Materials is a minimum-melting composition of two or more organic or inorganic PCMs, each of which melts and freezes congruently forming a mixture of the component crystals during crystallisation [15]. They possess a slightly higher volumetric storage density when compared to organic compounds. There is currently limited data available on the thermophysical characteristics of Eutectics, as the use of these materials are relatively new to thermal storage application.

A recent review on latent thermal storage for building applications notes that ‘PCM encapsulation is one of the ways which enables integration of PCM into buildings, and also prevents PCM leakage as well as protecting the PCM from interaction with the external environment and hence determines its long-term operation’ [16]. In the case of indirect PCM is an important component of the heat exchanger because it enables the heat transfer between the PCM and air. Therefore, optimised encapsulation will increase the overall performance of the system because it will lead to a faster thermal response and faster charging period. Also the strength, rigidity and fire resistance of the encapsulation needs consideration. There are a variety of PCM encapsulation techniques proposed and utilised by different researchers and offered by companies with various configurations and manufacturing materials. Some of these include aluminium panels, aluminium pouches, metal or plastic spherical balls, flat plates, plastic bags, different forms of plastic tubes, cylindrical pipes, PVC panels, shells, granules. [same paper as above]. PCMs encapsulation can be classified into micro and macro-encapsulations according to the container size:

- In microencapsulation; very small particles are contained inside solid and thin shells.
- In macroencapsulation, PCM are packaged in various containers’ configurations such as aluminium panels and pouches, and in most cases, the container itself acts as a heat exchanger surface.

Example of Operation of an Active Decoupled PCM System.

A typical operation of an active PCM, decoupled from building envelope, system is given in Fig. 7.7 and can be described as follows, following the time line over 24 h.

Midnight to 01:00—Night Purge—the fan runs at the highest speed setting for 1 h with the aim of flushing the room of stale air. Figure 7.7 shows that all temperatures

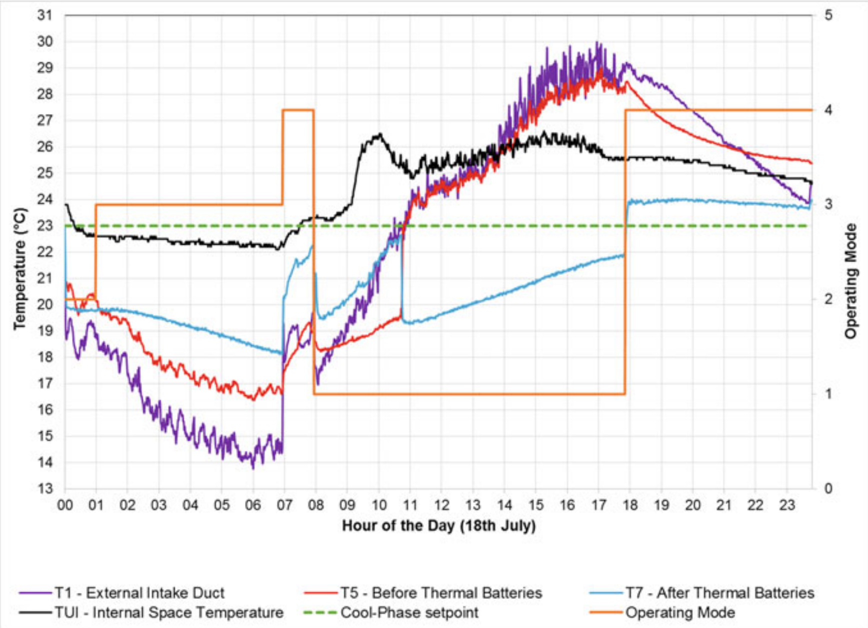

Fig. 7.7 Daily operation of the system presented in Fig. 7.6

within this period decrease including the Internal Space Temperature, TUI. It should also noticed that T1 (external intake duct) is the temperature of the sensor placed at the face of the intake duct. This sensor can be influenced by infiltration from the room if the plenum is not well sealed.

01:00 to 07:00—*Summer Night Charge*—During this period, the inlet and outlet temperatures of the LTES (T5 and T7, respectively) can be seen to decrease indicating that the LTES is being 'charged' as the external intake air is being passed through them.

07:00 to 08:00—*System Switched Off*—The system is turned off for 1 h in the morning in a period before the occupancy schedule begins. A crucial observation however, is that the internal space temperature (TUI) rises during this period which effectively can negates all the work done to cool the space during the night. The internal space temperature at 7:00 was well within the thermal comfort range and there was no risk of overcooling. Although this is a small temperature rise, it may influence the timing of peak internal temperatures later in the day.

08:00 to 18:00: Summer Day Mode: As TUI is left above the system's cooling set point temperature of 23 °C, the cooling mode is initiated immediately at 08:00. To begin with, the control system registers that the external intake temperature (T1) is still below the set point temperature, so in order to conserve the PCM TES charge, it uses the bypass route (see Fig. 7.6), to cool the conditioned space. Again during this period T5 and T7 readings are misleading as there is no air flow through the route of these temperature sensors, and so T1 is effectively the supply air temperature during this period. As the external temperature rises, T1 reaches the set point temperature of 23 °C at 10:41, at which point the bypass damper closes and the external air passes through the PCM TES cooling the external air to a lower temperature (starting at 19.3 °C). When the air flow path switches to the PCM TES route (see Fig. 7.6) it confirms that the previous readings of T5 and T7 when the fan is off or the bypass route are misleading. The temperature before the PCM TES (T5) rises sharply to meet very similar temperatures to the external intake duct (T1). Conversely, the air temperature after the PCM TES drops from its high temperature reading (likely influenced by the temperatures of the bypass route air), to a value only ~1 °C higher than when the PCM TES route was in use, at 07:00 when the Night Charge ended. After the PCM TES route is initiated, the PCM begins to absorb large quantities of heat from the incoming external air, as can be seen by the difference between T5 and T7—at 17:14 the temperature difference reaches its maximum at a 7.24 °C reduction. Despite being unable to reduce the temperatures to below the unit set point, throughout the PCM TES cooling period, the internal space temperature TUI is observed to have been efficiently stabilised by the PCM cooled air—even with rising external intake temperatures reaching 30 °C.

18:00 to 00:00: System Switched Off)–At 18:00 the conditioned period in the space ends, the system switches off and all temperatures converge to the same value. The system remains switched off until midnight where the process starts again.

The system was able to maintain comfortable conditions in a seminar room and an open plan office in the climate of south-east England [17].

7.2.4 Case Studies and Monitored Results

15 case-study buildings constructed after 2010 which include ventilative cooling were studied extensively as part of the work programme of IEA EBC Annex 62 and results reported in [18]. Of these, seven have heavy or very heavy constructions according to classification by (ISO 13790). They cover a variety of climatic conditions from Temperate with warm summers and no dry season (Cfb) (no 1 and 6) to Temperate, hot summers and no dry season (Cfa) (no 2), to Temperate with dry, hot summers (Csa) (no 4 and 5) and Cold with warm summers and no dry season (Dfb) (no 3). Three are retrofits (1, 3, 6) while two are residential (multiple no 2 and single house no 4).

1. Zero2020, Cork Ireland—office building—very heavy -retrofit
2. MOMA apartment buildings, Changsha, Hunan, China—residential—very heavy
3. University of Innsbruck, Austria—office building—heavy—retrofit
4. Zero energy certified passive house in Mascalucia—Sicily—residential – very heavy

5. CML kindergarten—Portugal—very heavy
6. Seminar room, University—medium with PCM - retrofit

A summary of the six case-studies with sensible thermal mass follows and more details can be found in [18].

Zero2020 is an office building in Cork, Ireland housing students and academic staff. It was retrofitted in 2012 and includes thermal mass in the form of exposed brick/concrete in the walls and ceiling—therefore it falls in the category of *passive sensible thermal storage strategy*. Ventilation provision is through single sided natural ventilation due to the cellular nature of the existing internal layouts and constraints imposed regarding continued operation of the existing building. Large opening heights are employed to promote buoyancy forces in hot summer periods. Some instances of cross flow exist in the open plan office space when openings are activated on both south and west façades. Cooling is available during occupied hours through the activation of the openings. A combination of occupancy level manual openings and high level automated openings is available for increasing ventilative cooling. A night cooling strategy is also available. The overheating risk was monitored and simulated. Annual simulations indicated that the total building level amount of hours greater than 25 °C was around 3% of the time annually. There were no hours in the typical year that was above 28 °C.

MOMA apartment building is located in the central China and was completed in 2012. The concrete ceiling radiant cooling panels with dedicated outdoor air system was utilized to cooling, heating and ventilation. The radiant ceiling system uses two ground source heat pump units as the cool and heat source. Therefore this system falls in the category of *activated sensible thermal storage strategy*. The mechanically ventilated system, with air inlet in the floo, supplies fresh air and exhaust air from the air outlet in the top of the kitchen and the bathroom. Thermal comfort was assessed through an occupant questionnaire, measurements in the building and simulations and indicates that 93% of the subjects consider acceptable thermal environment including neutral, slightly warm and slightly cool.

University of Innsbruck office building is a renovated building completed in 2014 and has achieved enerPHit standard of the Passive House Institute. The ventilation solution for the retrofit involved a concept of ventilative night cooling of the offices to guarantee high occupant comfort in summer. Newly developed automatically operable windows and air flow valves are key elements of the ventilation concept. The retrofit contained the installation of a completely new façade with automatically operable windows for natural ventilation and ventilative cooling. The exhaust air vents of the mechanical ventilation system can be used to increase the air flow from exterior to interior. The building includes thermal mass in the form of exposed brick/concrete in the walls and ceiling—therefore it falls in the category of *passive sensible thermal storage strategy.* Simulation showed that the retrofit reduces the risk of overheating to 0.5%. In total during 48 h per year temperatures rise above 26 °C. Monitoring in selected spaces in the building has confirmed these findings.

ZEB house in Mascalucia, Sicily is a new built house certified according to the Passivhaus standard. The building is conceived in order to minimize the energy need for heating and cooling; in particular, it exploits natural ventilation strategies such as cross-ventilation and night ventilative cooling. The building includes thermal mass in the form of exposed brick/concrete in the walls and ceiling—therefore it falls in the category of *passive sensible thermal storage strategy*. However it also includes an Earth-to-Air Heat Exchanger (EAHE) coupled to the mechanical ventilation system. Long term monitoring in the occupied house has revealed that while the external air temperature reaches peaks up to 36 °C, the internal air temperature shows much smoothed fluctuations, with the highest values around 28 °C. Since the mechanical ventilation was kept off during the whole period, the comfort levels were guaranteed exclusively by means of passive/low-energy strategies, that is: the operation of the solar shading systems and the activation of the thermal mass of the building.

The CML kindergarten is a small two-story building in two floors completed in 2013. NV air is introduced into the space through low level grilles or by windows opening on the façade and is exhausted in the center or back of the room, through one or two chimneys. Therefore, two different natural ventilation strategies could be employed: displacement ventilation (DV) and single sided (SS) ventilation. In DV systems air is introduced near the room floor with low velocity. Buoyancy forces induced by temperature differences between inflow and room air heated by internal gains promote airflow across the floor towards the heat sources where the ventilation air expands and moves upward. With the goal of maximizing thermal inertia, the walls are made of exposed concrete and have external insulation, therefore it falls in the category of *passive sensible thermal storage strategy*. Internal air temperatures have been measured and recorded in the main spaces; these long term measurements indicate that the total hours above 26 °C during occupied hours was 10%.

The seminar room, in the UK University building utilises PCM storage. This case study is presented in more detail below as an example of *active latent thermal storage strategy*. The seminar room was chosen for further study because of its use (computer laboratory) with higher internal heat gains than offices and general use spaces in the university.

The performance of the VC PCM system in maintain acceptable environmental conditions in the room was studied through field measurements; air temperature and relative humidity was measured in the room at 0.7 m as well as in different heights and in the terminal units. Figure 7.8 shows the temperature distribution over the year during occupied hours as well as the system's set point. With the exception of the winter period, where the setpoint of 24 °C was barely achieved, the system maintained well the temperature along the set point. The university was closed during the first week of January and due to that, an accentuated decrease in temperature can be seen. Figure 7.9 shows the stratification in the room between seating level and exhaust air; it also indicates the variation of one point with average temperature in the room which is small.

Figure 7.10 shows the results during weekdays (8:00–21:00) for the room for two cooling periods (May until September); temperature and relative humidity were averaged by all sensors at 0.7 m. Relative humidity is within a good range between 30 (apart from 3 h on one day in May) and 70% (apart from one day in August), the temperature did not exceed the upper thermal limit. In general, the seminar room has

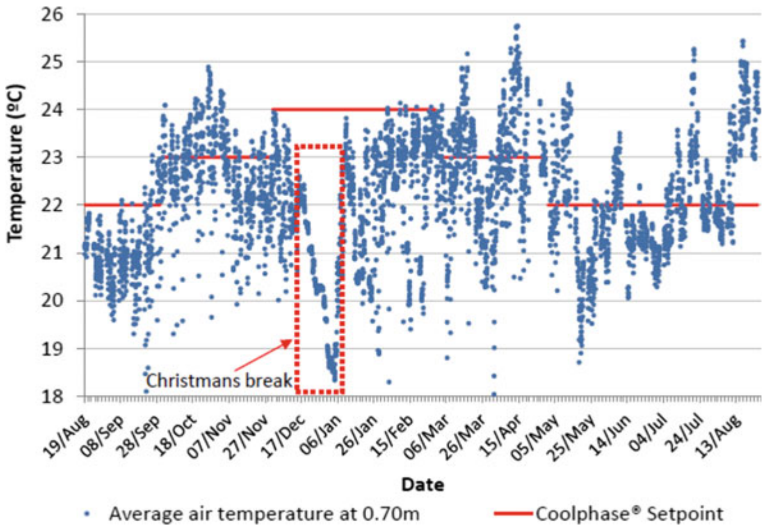

Fig. 7.8 Daily mean temperature and relative humidity from 8 AM to 8:59 PM from 19/08/2015 to 25/11/2015

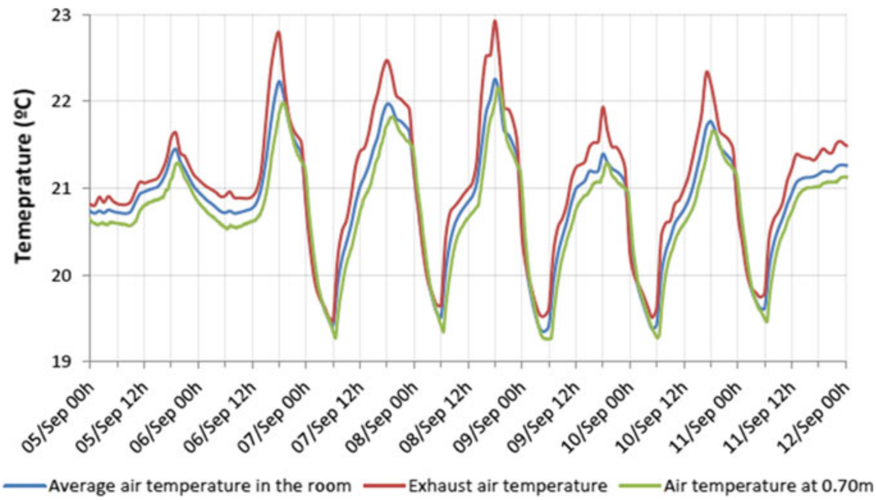

Fig. 7.9 Exhaust temperature, average of all sensors and temperature average at 0.70 m from 05/09/2015 to 12/09/2015

low solar gains because of the small area of windows and ground floor position. This favour the maintenance of the temperature in comfortable conditions during summer periods with full occupancy; for example during examination times in mid-May and mid-August 2016. However, some overcooling occurs for some hours (116 h (3%)) indicating that night purging might need more detailed control than relying

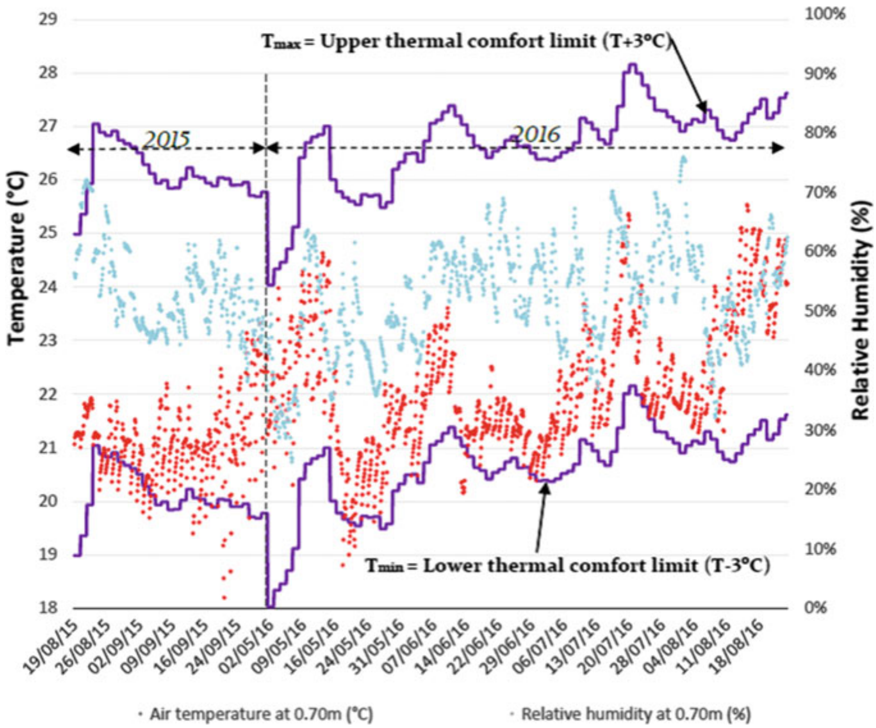

Fig. 7.10 Average temperature and relative humidity at 0.70 m for the cooling season and upper and lower thermal comfort limits bands

on a timer. Conversely, this discomfort can be solved simply by enhancing clo (e.g. wearing heavier clothes like a sweater or jacket).

Aimed to understand the temperature and airflow distribution in the seminar room, a CFD analysis was carried out. Figure 7.11 shows the temperature distribution at 1.2 m (seating person head height). It can be seen that temperature distribution is relatively uniform without cold or hot areas in the room. Vertical stratification can be seen in Fig. 7.12 with higher temperature above occupancy level.

In terms of energy consumption, the system includes a variable speed fan and motors to control the dampers resulting in low overall energy consumption. Electrical energy consumption in the seminar room was 91.7 kWh (0.78 kWh/m^2/y) in 2014 and 78 kWh (0.67 kWh/m^2/y) in 2015. In monetary terms, this will cost less than £ 10 per year (based on 2015 cost average of £0.104 per kWh for a medium size building [19]). Simulations with DTM program show an energy demand of 8.83 MWh (75.5 kWh/m^2/y) to maintain the same internal conditions. Therefore, the energy used by the system is a small fraction of the energy required by an AC system (the exact saving is dependent on the AC system and its COP). Annual electricity energy use intensity for secondary schools in the UK has a median of 51 kWh/m^2 [20] including electricity used for lighting and office equipment. This increases by 5 kWh/m^2 when

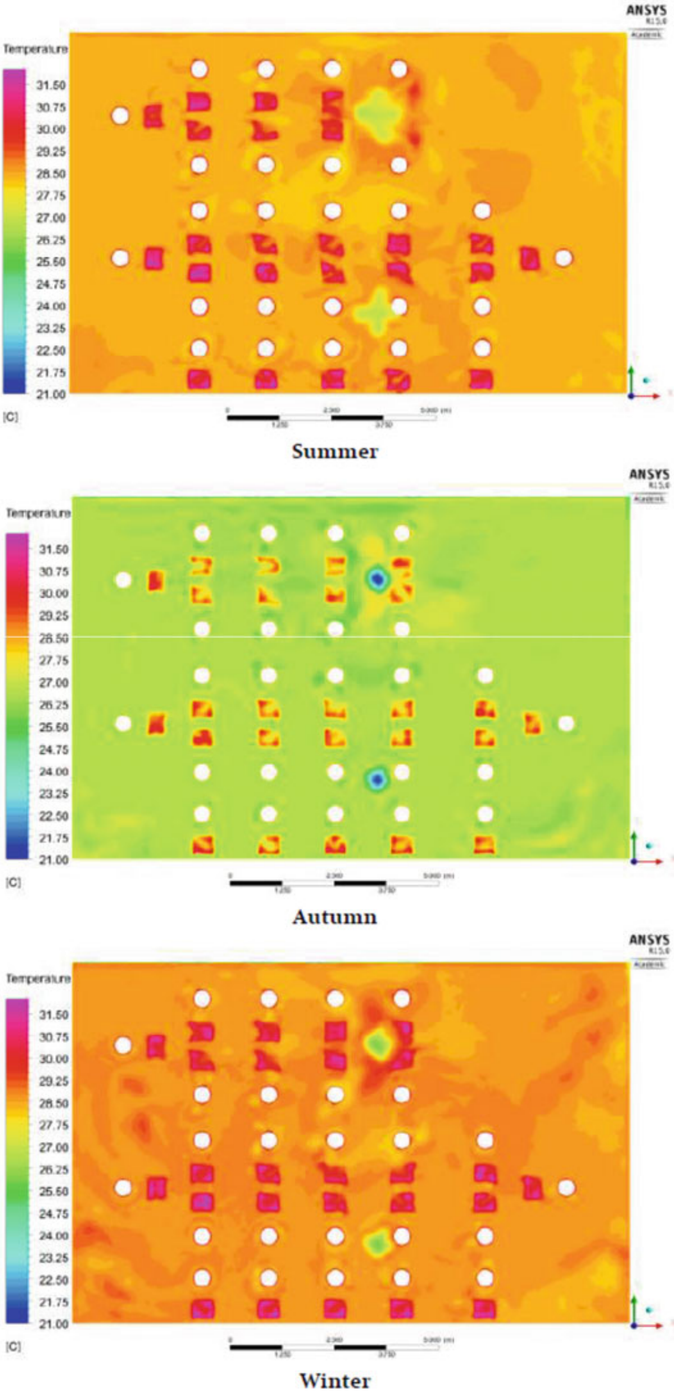

Fig. 7.11 Temperature distribution at z = 1.2 m

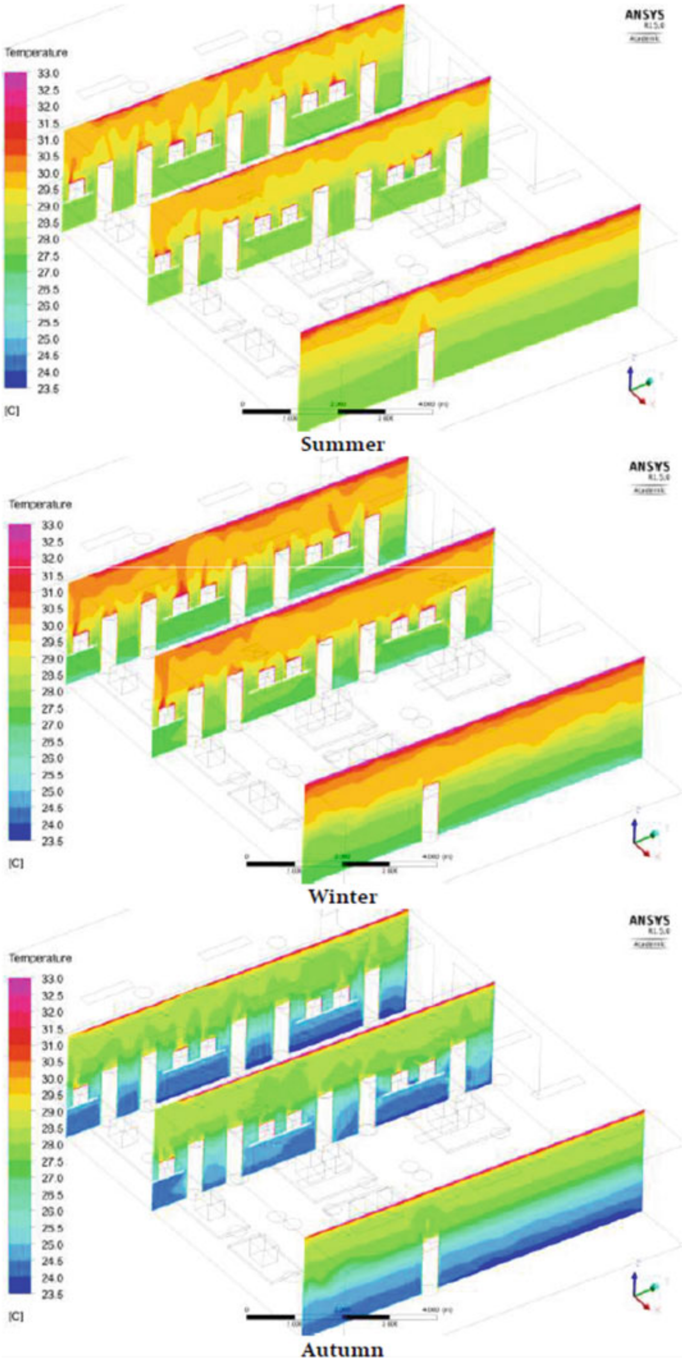

Fig. 7.12 Temperature distribution of rows 2x, 4 × and 7x

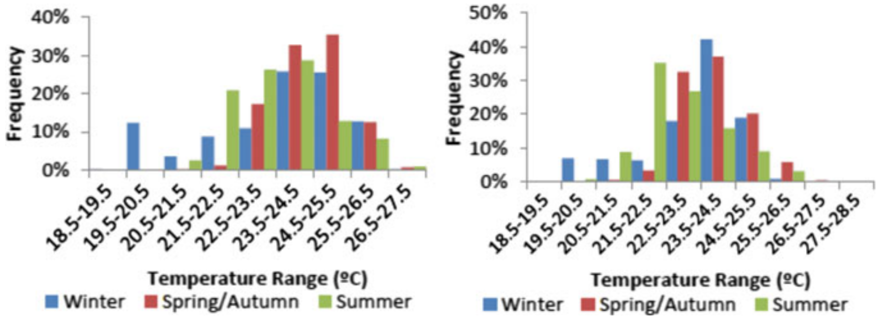

Fig. 7.13 Percent range of indoor temperature system data for weekdays of 2014 (left) and 2015 (right) from 8:00 to 21:00

moving from 'heating and natural ventilation' to 'heating and mechanical ventilation' buildings, indicating the typical magnitude of energy use by mechanical ventilation. CIBSE TM57 [20] presents good case-studies with cooling energy intensity of 12.5 kWh and 3.5 kWh/m^2. Therefore, the energy needed to operate the system is small compared to available benchmarks.

Figure 7.13 presents weekday indoor temperature frequency in percentage from 8:00 until 21:00 in 2014 (left) and 2015 (right). In 2014, temperatures of 24 ± 0.5 °C were more frequent for winter and summer (25 and 28% respectively) and 35% for 25 ± 0.5 °C for Autumn/Spring. In 2015, the system maintained the seminar room in the set-point temperature more frequently during summer (35%) and winter (42%). During Spring/Autumn, the room was slightly warmer than the set-point (37% for 24 ± 0.5 °C). Figure 7.13 also shows that the system maintained the room temperature between 21.5 and 26.5 °C for most of the time in 2014 (93%) and between 21.5 and 25.5 for 88% in 2015. In this case, occupants can easily adapt by increasing or decreasing clothing.

7.3 Cooling Potential Calculation Approaches

7.3.1 Cooling Potential Feasibility Tools

As mentioned in Sect. 7.2 thermal mass describes a material's capacity to absorb, store and release heat and should be included in the modelling of ventilative cooling coupled with thermal storage. For this, design and simulation tools that combine thermal and airflow models are necessary. These are outlined in [21]. Such tools were used in the evaluation of case-studies of ventilative cooling with thermal mass presented in Sect. 7.3. Tools used were:

1. Zero2020: At detailed design stage a whole building energy model was developed to investigate the risk of overheating for the building as well as specification of ventilation opening areas for each zone. The code and software was Apache/IESVE for thermal analysis and IESVE Macro Flo for airflow modelling. CIBSE Admittance method was used for concept design and overheating risk assessment. Thermal admittance is fully described in EN ISO 13786:2007 [22]. This framework provides the basis for the CIBSE 'cyclic model' for calculating cooling loads and summertime space temperatures [23] which has been incorporated in compliance tools.
2. MOMA apartment buildings: CFD analysis was used to guide the design of the heating, cooling and ventilation systems.
3. University of Innsbruck: The Passive House Planning Package (PHPP [24]) was used for the scope development to define building element quality and energy performance, followed by the dynamic simulation programme DYNBIL for concept design thermal analysis (also developed by Passive House Institute) while TRNSYS was used for more detailed thermal analysis.
4. Zero energy certified passive house: Dynamic thermal modelling using EnergyPlus.
5. CML kindergarten: Dynamic thermal modelling using EnergyPlus.
6. Seminar room, UK: IESVE software was used to design the system. The case-study include a PCM thermal storage; ISEVE has a plug-in [25] that enables the user to design the system by changing parameters such as the system type, size and number of units required according to the heat gains.

Research and development of tools and approaches to the modelling of thermal mass within dynamic and simplified tools is continuing. Recent results discuss the representation in different simulation models [26, 27]; they note that there are several simplified, usually simple dynamic, quasi-steady state or steady state methods used for the calculation of energy use in buildings, such as the BS EN ISO 13790: 2008. They also note that there is a difference between the thermal mass of the fabric and the effective thermal mass (see also Sect. 7.1). The term effective thermal mass is used to define the part of the structural mass of the construction which participates in the dynamic heat transfer.

These approaches have been integrated in some compliance tools. For example, SAP (standard assessment procedure for energy rating of dwelling [28]) in the UK incorporates thermal mass with the Thermal Mass Parameter (TMP) which is required for heating and cooling calculations. This is defined as the sum of (area times heat capacity) over all construction elements divided by total floor area. It can be obtained from the actual construction elements of walls, floors and roofs (including party and internal walls, floors and ceilings).

The k values are used to calculate the TMP variable (Thermal Mass Parameter), worksheet (35), which is used to characterise the thermal mass of the building. It is:

$$TMP = \frac{\sum \mathrm{k} x A}{TFA}$$

where,

TMP = thermal mass parameter, kJ/m^{2}K.

K = Heat capacity, kJ/m^{2}K, effectively it is the measure of the heat capacity per unit area in kJ/m^{2}K of the 'thermally active' part of the construction element.

A = surface area of all walls, floors and roofs bounding the dwelling (including party walls and floors/ceilings) together with both sides of all internal walls and floors/ceilings, m^2.

TFA = TFA is the total floor area of the dwelling.

Indicative values of TMP are: Low 100 kJ/m^{2}K, Medium 250 kJ/m^{2}K, High 450 kJ/m^{2}K.

7.3.2 Estimation of Night Cooling Potential

The cooling potential feasibility tool developed by IEA EBC Annex 62 [29] includes an estimation of the night-time cooling potential over the night following the days when direct ventilative cooling is not useful because of high daytime ambient temperature. Although thermal mass is not included in the calculations, the tool can give very quickly an indication on whether night ventilation can contribute to comfort under the specific location conditions and building type considered so as the designer can decide on the possibility of inclusion of thermal mass.

The tool was used to examine a number of locations with different climatic conditions and the results are summarised in Table 7.1. It should be noted that the same building with the same thermal characteristics was used for this analysis so that there is a direct comparison; the inputs are shown in Fig. 7.14 for the Wuhan, China location where it can be seen that U-values indicate a well insulated envelope with relatively low internal gains and good shading. In reality, this will not be the case for some of locations but they were kept the same for simple comparison. Figure 7.15 shows the nighttime ventilation potential for Wuhan China. For the climatic conditions in Wuhan, (humid subtropical with cold winter and hot summer), Fig. 7.14 shows that venitlative cooling is a good solution; increased airflow (4.5 + /2.3 ACH) can provide required cooling but also there are times in the summer where additional cooling is required. Figure 7.15 shows that night ventilation can offset between 2.5 and 8 W/m^2 of internal heat gains during the times that additional cooling is required.

7.4 Conclusions

This chapter focussed on the coupling of ventilation with thermal mass integrated in the building or the ventilation system in the form of latent thermal storage, to reduce cooling demand. It outlined the principles and presented results of operational case-study buildings extracted from building studied as part of IEA EBC Annex 62 on ventilative cooling.

Table 7.1 Nighttime ventilation cooling potential for a small office in different climates

Location	Climate type Koppen	Diurnal temperature swing (K)	Nightime cooling degrees (K)	Ventilation rate required (ACH)	Heat gains offset (W/m^2)
Dublin—Ireland	Oceanic Cfb	2–3	0–280 (Aug)	3 ± 1	9 (Jul and Aug)
Wuhan—China	Humid subtropical Cfa	2–3	120 (May)–1800 (Nov)	4.5 ± 2.3	2.5 (July)–8.5 (Nov)
Shillong, India	Warm and temperate Cwb	3–6	220 (Feb)–2000 (May)	5.4 ± 2.3	6 (Jul)–12 (Dec)
Dubai, UAE	Arid hot BWh	3–4	400 (Jul)–2200 (Dec)	5.5 ± 2.5	1.0 (Jul)–8 (Jan)
New Delhi, India	Semi arid BSh	3–6	1000 (Dec)–3800 (Nov)	5.3 ± 2.4	3 (may-aug)–12 (Dec)
Dakar Senegal,	Semi-arid BSh	1.5–2.5	450 (Apr)–2200 (Dec)	6.4 ± 2.5	6.5 (Jan)–4 (Jul)
Manaus—Brazil	Tropical monsoon—humid hot Am	2–3	1500 (Feb)–2200 (Apr)	6.7 ± 2.7	3.5 (Aug)–5 (Apr)
Kingston Jamaica -	Tropical savanna–Aw	2–3	1200 (Jul)–2200 (Jan)	6.6 ± 2.5	2.5 (Jul)–5.5 (Jan)

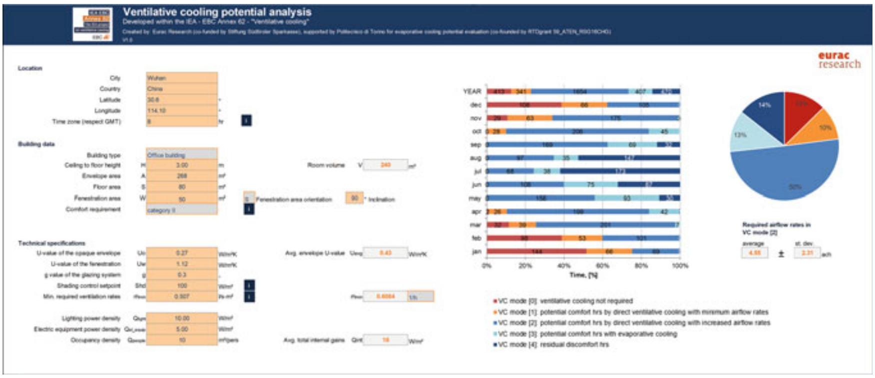

Fig. 7.14 Results from ventilative cooling potential tool for an office building in Wuhan, China

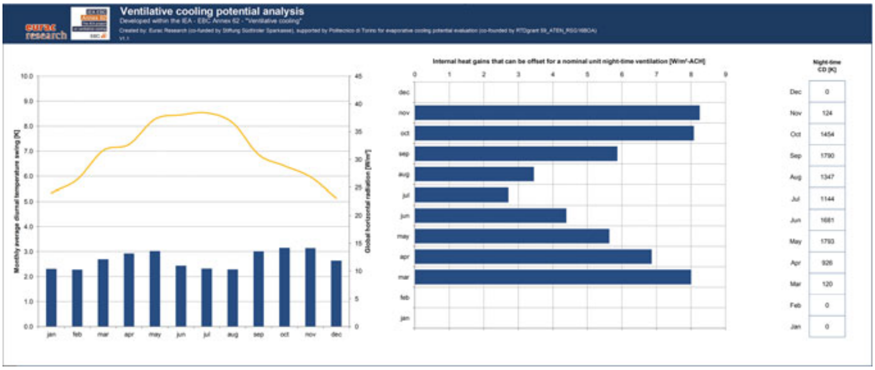

Fig. 7.15 Results by the ventilative cooling potential tool on the impact of night ventilation for an office building in Wuhan, China as presented in Fig. 7.14

From the principles and results presented the following conclusions can be drawn:

- Ventilation cooling using thermal mass often uses favourable external conditions during the night to charge the thermal mass, termed night ventilation. An analysis for different climates from oceanic to arid-hot to humid subtropical presented in Sect. 7.4 indicated that required night ventilation rates are feasible to achieve, with less than 9 ACH in most extreme case. This can offset up to 9 W/m^2 of internal heat gains during the following day.
- Presented case-studies have used a variety of design tools mostly dynamic thermal models. There is a need for more simplified tools which couple ventilation with thermal mass. Compliance tools in many countries ignore the beneficial effect of thermal mass or incorporate it in the form of an overall correction factor which in most cases does not capture monthly (let alone daily) variations.
- Sensible thermal storage within the exposed building fabric is established as a 'default' principle for passive cooling design.
- Sensible thermal storage decoupled from the exposed building envelope and activated through a fluid medium (air or water) is well researched and also applied to operational buildings.
- Latent thermal storage for building applications using phase change materials is well researched but there are few examples of operational buildings which couple it with ventilation systems. The results of a study of such an operational system have been presented, describing the cycles of charging/discharging of the thermal storage and presenting the resulting measured environmental conditions in the space. For the temperature climate of south England, it was shown that ventilative cooling with phase change materials storage is a promising strategy.

Moving forward, there is a need for thermal mass to be explicitly considered in national building regulations and compliance tools so that it is considered by designers and consequently be implemented in more buildings. However, limitations imposed by climatic conditions, available space for thermal storage and the cost of operation in case mechanical ventilation is needed to activate the thermal mass are additional considerations.

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Chapter 8
Ventilative Cooling in Combination with Other Natural Cooling Solutions: Direct Evaporative Cooling—DEC

Giacomo Chiesa and David Pearlmutter

Abstract This chapter analyses the potential combination of ventilative cooling solutions with direct evaporative cooling (DEC) systems. The focus is on passive downdraught evaporative cooling (PDEC) towers, whose performance is described based on the analysis of monitored results. The main design aspects of PDEC towers are explained, including basic relationships and support tools for system optimization. A series of case studies is reported, illustrating different integration strategies and providing a series of examples for designers. Finally, a simulation-based approach to analysing the local potential of PDEC to reduce thermal discomfort in naturally ventilated buildings is introduced, providing a method by which DEC systems can be integrated in building projects from the early-design phases.

8.1 Introduction

Ventilative cooling, such as controlled natural ventilation (CNV), is a strategy to consistently reduce the amount of energy required for space cooling and ventilation (IAQ—indoor air quality) by exploiting natural cooling potential due to heat gain dissipation thanks to air temperature differences between environmental and internal air and considering convective exchanges with air and the human body. Unfortunately, in some locations environmental air temperature in the summer period is higher than comfort thresholds, reducing the local potential of ventilative cooling techniques. Nevertheless, the possibility to adopt CNV or hybrid ventilation in combination with additional heat sinks may constitute a valid challenge to increase the potential of ventilative cooling systems and the number of application hours. Prominent among these strategies are evaporative cooling solutions, which are based on

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the fact that significant quantities of sensible heat are converted to latent heat during the process of water evaporation [1].

Evaporative cooling is a traditional cooling technique in dry and hot locations, with historical examples having been reported from as far back as ancient Egypt and Persia [2]. The wide variety of historical applications includes elements such as fountains, artificial grottos and nymphaea, water basins, open canals, and sprayers [3]. It is possible to consider, for example, the internal evaporative system in the Ziza palace in Palermo, Italy, or a similar system in Red Fort, Delhi, India, or even the 'canòpo' spaces of Roman villas in which water basins are linked with water fountain games—e.g. Villa Adriano in Tivoli, Italy. Furthermore, several Renaissance and Baroque villas used large fountain systems—such as the Neptune Fountain and the Water Organ in Villa d'Este, Tivoli, Italy—or artificial Grottos and nymphaeum spaces with water tanks and small fountains—such as the nymphaeum of Villa Giulia in Rome, Italy, or the Grotto of Thetis, Versailles, France.

The contemporary application of evaporative cooling systems for space cooling can be traced to two separated origins in the U.S., as documented by [4] and described in [5]. On the one hand, there was a need in the eastern states for cold humid air in textile buildings, and this led to the use of water sprayers as direct way to reduce air temperatures—creating the basis for air cleaning systems that became widespread in a range of industrial applications. On the other hand, indirect as well as direct evaporative cooling systems were developed in the hot-arid southwest and by 1930 had been implemented in Arizona and California for both residential and tertiary buildings. In parallel, the publication of psychrometric tables in the early 1900s by the U.S. Weather Bureau opened the way for the scientific definition of evaporative cooling base expressions (i.e. Carrier's paper of 1911) [6].

The adoption of evaporative cooling in mechanical systems since the beginning of the 20th century is reflected in U.S. patents on evaporative coolers, such as that of Stuart W. Cramer in 1906 for air conditioning textile spaces. It is still the basis for various direct and indirect HVAC-integrated technologies (see for example the review on solar cooling reported in [7], including both evaporative and desiccant air conditioning systems). Prominent among low-energy mechanical systems is the example of the "desert cooler" commercialized in the 1920's [8], in which a primary airflow is directly humidified by passing through a wet pad evaporator. In contrast, several indirect evaporative solutions are used in mechanical cooling systems, including those which are coupled with fan coil distribution systems, thanks to the integration of an evaporative chiller in order to cool a fluid that is further used to cool spaces.

This chapter focuses on passive evaporative cooling systems, which can be divided into direct evaporative cooling (DEC) and indirect evaporative cooling (IEC) solutions—see for example Fig. 8.1. Considering the overall theme of the book, emphasis is placed on techniques connected with ventilative cooling and consequently on DEC systems such passive downdraught evaporative cooling (PDEC) towers. Among IEC solutions, however, it is possible to mention "psychrometric" roof ponds in which a shaded and naturally ventilated water layer can reduce the internal temperatures of the coupled space to values near to the ambient wet bulb temperature—see for example [9].

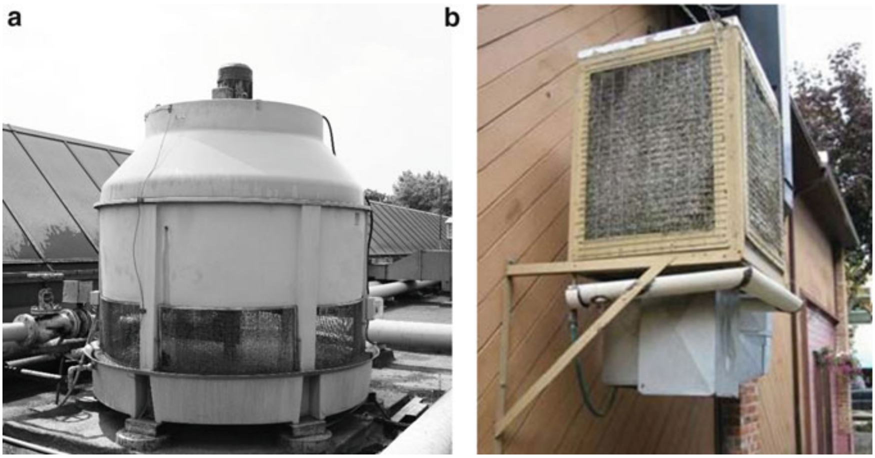


Fig. 8.1 **a** an indirect evaporative cooling (IEC) chiller; **b** a direct evaporative cooling (DEC) system (known as a “desert cooler” or “swamp cooler”)

The chapter is structured as follows.

Section 7.2 describes in detail the physical principles of DEC (adiabatic humidification), including the use of graphical representation on a psychrometric chart. Different types of DEC systems are described (e.g. shower towers, misting towers, cooling towers, porous media, etc.), defining the main characteristics and functioning principles. Furthermore, the main calculation approaches, including simplified regression formulas and specific tools, are described and briefly compared. Moreover, the main design issues connected to the dimensions of DEC systems in specific contexts and building integration strategies are defined. Finally, a simplified design approach is suggested. Section 7.3 describes specific methodologies for calculating the local potential of passive downdraught evaporative cooling systems for reducing the environmental air temperature and improving the potential of natural controlled ventilation solutions. This analysis is based on the local climate conditions, and is applied to a large set of locations to highlight those sites in which DEC may have a high potential without the need for pre-dehumidification treatments of the external air. Finally, Sect. 7.4 provides a brief concluding summary of the chapter.

8.2 Direct Evaporative Cooling Systems: Main Principles

As mentioned previously, evaporative cooling systems can be divided into two types: direct and indirect. Direct evaporative cooling (DEC) is based on the direct evaporation of water into the primary airflow, while the indirect evaporative cooling (IEC) utilizes the evaporative cooling of a secondary fluid that exchanges sensible heat with the primary airflow. While direct solutions imply the increase of the absolute humidity of the treated air, indirect systems may avoid this—thereby lowering the dry bulb temperature of the treated air without increasing its moisture content (e.g. [10]). Considering the applicability of DEC for ventilative cooling purposes, this section focuses mainly on direct solutions. The physical principles of DEC systems are introduced in Sect. 7.2.1, followed by a survey of system types (Sect. 7.2.2), simple calculation approaches (Sect. 7.2.3), and design issues (Sect. 7.2.4).

8.2.1 DEC Physical Principles

Direct evaporative cooling solutions are based on the introduction of water into an airflow in order to saturate the air by evaporation (converting liquid water to gaseous vapour) and consequently reducing the temperature of the air stream and/or of the wet surface. It should be emphasized that this process, also called adiabatic saturation, does not change the total thermal energy of the system. The water vapour embodies latent heat, and may, in fact, condense—causing an inverse temperature trend. Even if the moisture content—also known as the absolute humidity or mixing ratio (measured in grams of water vapour per kilogram of dry air)—is small in comparison to other components of the air, this moisture is essential in atmospheric processes [1]. The absolute humidity ranges from 0 g/kg to a maximum value which varies in relation to air temperature and pressure levels. A commonly used index to define the amount of water vapour referring to this range is the relative humidity (RH) which is a percentage describing the amount of water vapour in the air with respect to the saturation water vapour quantity (100% RH) at the same dry bulb temperature (DBT).

Other essential variables in psychrometric studies are the (a) the dew point temperature, which corresponds to the temperature to which air at a fixed moist moisture content has to be sensibly cooled in order to reach 100% RH, and (2) the wet bulb temperature (WBT), which is the minimal temperature that can be reached with an adiabatic (i.e. fixed enthalpy) saturation process, cooling the air solely by the addition of water vapour through evaporation. At both of these points the air becomes saturated, resulting in the condensation of water vapour into liquid water. The cooling of air to its WBT reflects the fact that DEC is an isenthalpic process—see also [11]. Figure 8.2 shows these variables on a simplified version of a psychrometric chart based on Carrier studies—for an advanced description of physical processes in evaporation and desiccant processes see [12].

Considering these basic principles, it is possible to describe the effect of a DEC system as an adiabatic cooling process, "moving" the condition of the air along a line of constant enthalpy on the psychrometric chart (Fig. *). Under specific environmental conditions, a DEC system can convert the thermal state of the air into one that is considered comfortable—a state that can be visualized as the passing of this line of constant enthalpy through the "comfort zone" [13]. Figure 8.3 describes this process with a simple graphical representation of the phenomenon (Fig. 8.3a), and the plotting of monitored points representing the condition of the air before and after

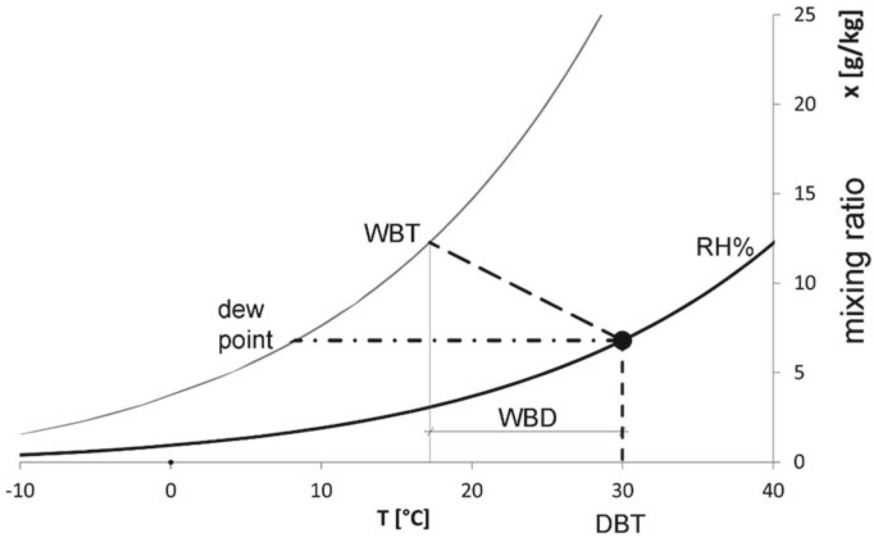


Fig. 8.2 Principal variables reported in a schematic representation of a psychrometric chart. WBT = wet bulb temperature, DBT = dry bulb temperature, WBD = wet bulb depression

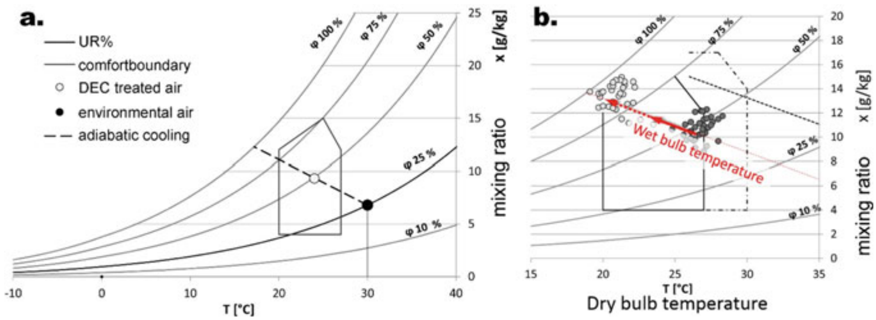


Fig. 8.3 **a** adiabatic cooling principles and DEC potential in reaching comfort; **b** the same principle illustrated by monitored data from an experimental DEC tower (inlet and outlet conditions), PoliTO, Turin

treatment in a PDEC tower (Fig. 8.3b). This basic approach was also used to define the applicability of DEC in bioclimatic comfort charts such as that of Givoni-Milne [14, 15].

Considering ventilative cooling applications, DEC is principally linked to desert coolers to treat intake air to be distributed in internal spaces, or to PDEC solutions in which little or no mechanical means are used to circulate the air—which is achieved instead through passive buoyancy forces [16, 17]. The expected effect of a PDEC tower in cooling an air flow is represented in Fig. 8.4. The graph illustrates the ambient air's DBT and corresponding WBT, as well as the temperature of the air after a passive DEC treatment.

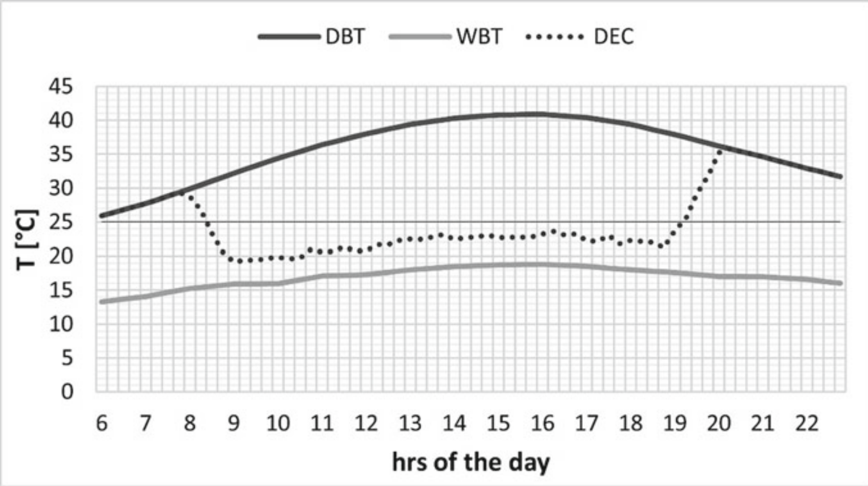


Fig. 8.4 Expected DEC treatment effect on environmental air for ventilative cooling purposes—typical climate conditions (Meteonorm v7.11 TMY), 21st June in Tucson, Arizona, considering a PDEC effectiveness around 0.8

8.2.2 PDEC System Types

Passive downdraught evaporative solutions may be classified according to the technological systems used for the evaporation of water in the treated airflow. According to Ford et al. [18], it is possible to identify four PDEC types: i. cool tower (wet pad); ii. shower tower (nozzle); iii. Misting tower (nebulizer); iv. porous media. Furthermore, a fifth type was also defined including hybrid systems in which an evaporative chiller located on the upper part of a building indirectly cools the air and consequently activates a natural downdraught, cooling the spaces below. The indirect approach allows for potential installations even under humid climate conditions (see for example commercial solutions such as Gravivent® or G-Therm®).

Nevertheless, focusing on direct systems, it is possible to divide PDEC solutions into two main classes: the first in which water is directly injected into an airflow—(e.g. shower and misting towers), and the second in which air passes through or close to a surface which is maintained in a moist condition—i.e. direct evaporation from wetted surfaces.

In the first case, nozzles or sprayers are needed, with or without water recirculation. In the second case, some solutions are nozzle-based (e.g. cool towers), while others (e.g. some porous media systems, such as the external columns of the Spain Pavilion at Zaragoza EXPO 2008) can be based on water basins and capillarity or on thin-layers of water flushing on porous surfaces.

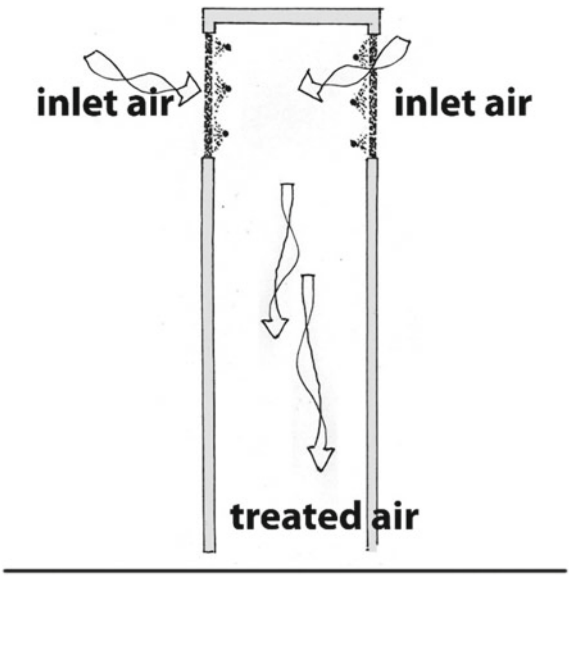
Considering direct evaporation from moist surfaces, one of the most commercially diffused PDEC systems is the cool tower: a system based on *wet pads*. In this solution, the water is sprayed on a pad that can be made from treated cellulose.

The primary airflow comes in contact with this pad, which acts as an evaporative exchanger. Several commercial wet pad solutions are presently on the market, in some cases coupled with fans to increase the airflow. Examples of PDEC wet pad towers are Cunningham and Thompson's experimental tower at the University of Arizona (1986) [8, 19], the Visitor centre at Zion National Park, Utah, U.S. [18], the MOMRA Environmental Rowdah project in Riyadh, Saudi Arabia [20] and the office building housing the headquarters of Botswana Technology Centre, South Africa [21]. Figure 8.5 illustrates a sample scheme of a cool tower system.

In contrast, *porous media* are systems in which materials such as porous ceramic surfaces are maintained in a saturated condition while exposed to the primary airflow, in order to reduce the air DBT thanks to evaporation. Several bioclimatic archetypes of this technique may be found in traditional Indian, Greek and Arabian buildings. Recent examples can also be seen, such as the above-mentioned Spanish pavilion at the EXPO of Zaragoza. This technique may allow for the operation of DEC systems even when the quality of the water is poor.

Direct spray systems work in a similar manner, by using water nozzles to evaporate water in the primary airflow. Nozzles are located at the top of the PDEC tower, generating a vertical downdraught airflow (negative buoyancy forces). The treated airstream flows down naturally, due to the progressive reduction in DBT and high relative density, the increase in its humidity ratio, and due to motion transfer between un-evaporated drops and the airflow—see the equations reported in [1]. Mechanical fans may be used to increase the volumetric flow rate of treated air, in accordance with IAQ (Indoor air quality) and cooling requirements. Figure 8.6a shows a sample functional scheme of a nozzle-based PDEC system. A water collection system can be used for the recirculation of non-evaporated water. In addition to systems with a

Fig. 8.5 Sample scheme of a cool tower system



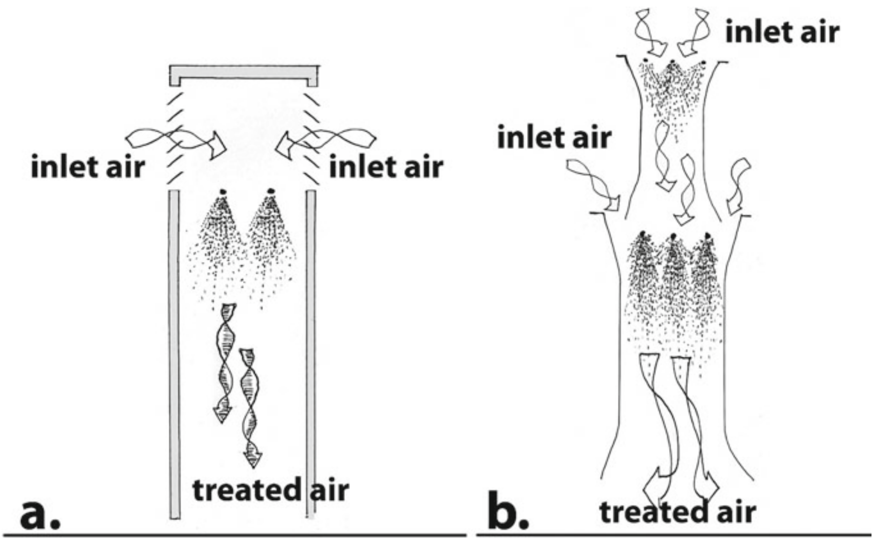


Fig. 8.6 **a** Sample scheme of a direct spray system; **b** sample scheme of a multi-stage spray tower system

single evaporator line, additional solutions have been investigated including a two-stage spray lines disposed vertically [9, 22]—see the sample scheme reported in Fig. 8.6b.

Among direct spay systems, misters and nebulizers generate water drops with smaller diameters, and if correctly designed can allow for full evaporation of the sprayed water—reducing the amount of water waste and the connected risk for legionella [23]. Small drops in fact accelerate the evaporation process due to their larger surface to volume ratio and hence their larger area of contact with the air. Furthermore, when misting towers are used, lower distances are needed between the tower inlet and the outlet openings connecting the PDEC tower with the space to be cooled [18]. Evaporation occurs, in fact, in the first few meters in height. However, this type of nozzle generally requires pumps working at higher pressure than those used in shower towers and is more susceptible to clogging. These towers may also show a lower effectiveness, not fully covering the WBD, even if they are designed to modulate water flows with respect to environmental conditions [1, 24].

In contrast, shower towers use a relatively coarse spray generated by nozzles characterized to produce a larger drop size. This system typically has a higher effectiveness than misting towers, but large quantities of residual non-evaporated water have to be collected at the base of the tower, resulting in a large risk for bacteria proliferation. A sample misting tower system is the one installed in the Malta Stock Exchange (a hybrid system), while an example of a shower tower (combining a range of sprayer types with different drop sizes) is the one installed at the Blaustein Centre for Desert Studies in Israel—see Fig. 8.7. Further examples are the shower tower in the Miele Showroom at Johannesburg in South Africa [25], and the shower towers

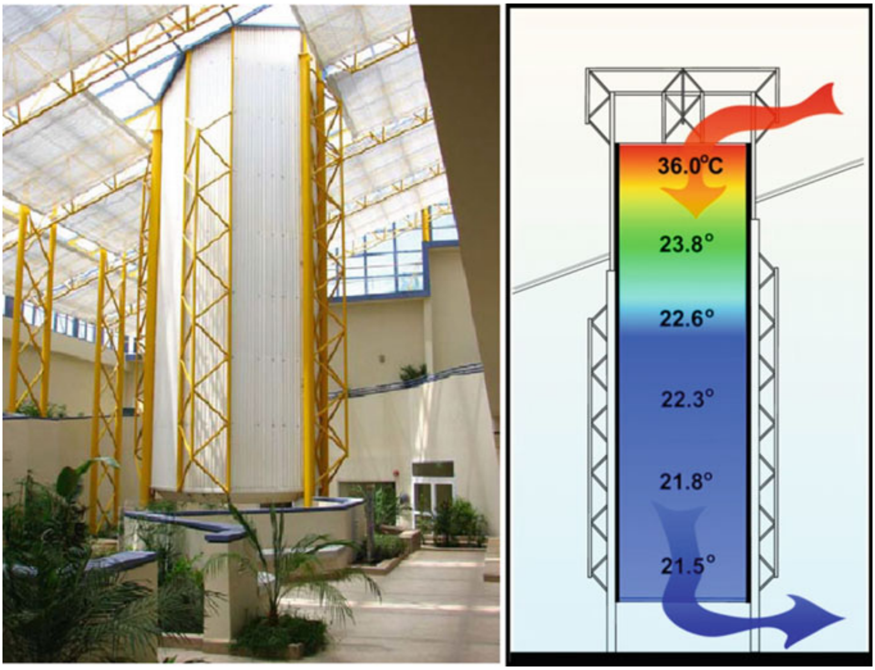


Fig. 8.7 The shower tower in the atrium of the Blaustein International Centre for Desert Studies in Israel (Photo courtesy of D. Pearlmutter) with schematic cross-section showing typical temperature profile

at the Council House office building in Melbourne, Australia. Figure 8.8 illustrates monitored data from a PDEC tower installed in a University laboratory, PoliTo, Turin, Italy equipped with a shower system [26].

8.2.3 DEC Simple Calculation Approaches

In order to simulate DEC systems for design purposes, different calculation approaches are possible. In particular, advanced simulations may be performed using CFD (Computation Fluid Dynamics) software [28], but such modelling requires specialized knowledge and incurs high computational costs when fully adopted in small/medium building solutions—see also the discussion in [29, 30]. Furthermore, the CFD simulation of an enthalpy exchange requires additional capabilities related to ventilative cooling, which are not provided in every commercial software package [28]. For this reason, the present chapter describes a number of documented calculation methodologies that have been recently validated using experimental data [23, 30].

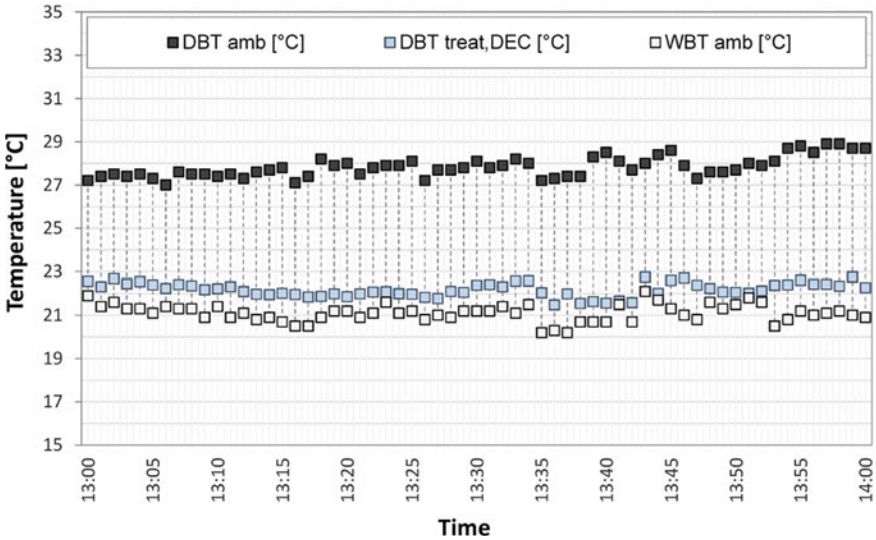


Fig. 8.8 Sample monitored values of inlet and outlet DBT (shower tower), and calculated WBT using the Stull expression [27]

Several studies have been reported in the literature about the development of simple calculation approaches to estimate the temperature (and the humidity ratio or RH) of an airflow following a DEC treatment. In particular, one of the more effective expressions to simply evaluate the potential of a PDEC tower is given in Eq. (8.1), as originally reported by Givoni [8, 31, 32] and based on analyses performed on the cool tower installed in an experimental building at the University of Arizona in Tucson [19]. This specific formula is also at the base of DEC simulation in EnergyPlus, and in particular is used in the CelDekPad module—see [33, 34]. Although Eq. (8.1) was developed for cool towers, it is possible to use it to predict the effects of shower and misting towers, as demonstrated with experimental data [26, 30].

$$DBT_{tr.air} = DBT_{in.air} - \varepsilon \cdot (DBT_{in.air} - WBT_{in.air}) \tag{8.1}$$

where the subscripts $DBT_{\text{in.air}}$ and $DBT_{\text{tr.air}}$ refer respectively to the psychrometric condition of the air entering the PDEC system (inlet) and to the condition of the outlet airflow after a PDEC treatment. The coefficient ε is the DEC effectiveness, a value representing the correlation between the inlet-outlet dry bulb temperature (DBT) difference and the environmental WBD, which represents the DEC potential—see Eq. (8.2). This relation is a synthetic index of a given PDEC's performance, and it is function of tower design configuration, site, and environmental conditions. As was suggested by Givoni, the DEC effectiveness of a system can be calculated using an early short-term monitoring. DEC effectiveness is, in fact, the slope of a linear regression line passing through the origin evaluating the difference in DBT between inlet and treated air plotted as a function of the correspondent WBD [8]. This calculation approach is especially useful when installing a new system in a given location, in order to correctly dimension it. In fact it is possible to make preliminary tests with a simple tube tower at an adjacent site to optimise the local effectiveness, and use this value to define the expected outlet conditions of a treated airflow using TMY (typical meteorological year) hourly data—see in particular the detailed approach described in [26]. Nevertheless, as was suggested in several studies [8, 30], a preliminary DEC effectiveness between 0.7 and 0.8 can be assumed as a general reference for early-design purposes.

$$\varepsilon = \frac{DBT_{in.air} - DBT_{tr.air}}{WBD_{in.air}} \tag{8.2}$$

Further expressions have also been developed based on experimental data. For example, Givoni [8, 35] developed an equation—see Eq. (8.3)—to calculate the expected outlet DBT by a shower PDEC tower. This equation also includes the water flow and the tower height, which are essential parameters for the definition of direct spray systems especially when no preliminary monitored data are available to calculate a more specific DEC effectiveness.

$$DBT_{tr.air} = DBT_{in.air} - WBD_{in.air}(1 - exp(-\varepsilon \cdot H))(1 - exp(-0.15 \cdot WF)) \tag{8.3}$$

where H is the tower height [m] and WF the rate of water flow [l/min].

Although Eqs. (8.1) and (8.3) are based on DEC effectiveness, it is also possible to estimate the treated DBT by using adapted expressions, which are independent of this specific value [30]. In particular, Eq. (8.4) [8] and Eq. (8.5) [35] report two alternative expressions for Eq. 8.3 (shower tower) whose definition was based on experimental data analysis. These expressions are principally conceived for early-design purposes, and the calculation approach can be coupled with EnergyPlus [35].

$$DBT_{tr.air} = DBT_{in.air} - WBD_{in.air}(1 - exp(-0.8 \cdot H))(1 - exp(-0.15 \cdot WF)) \tag{8.4}$$

where the DEC effectiveness is assumed as 0.8, a value that was demonstrated to be a correct indicator for early design purposes of PDEC towers on different experimental databases and for different expressions—such as Eqs. (8.1), (8.3), (8.4) and (8.5)—with a statistical accuracy of 86% based on different indicators (MBE, RMSE, U95, TT, R^2) [30].

$$DBT_{tr.air} = DBT_{in.air} - (0.9 \cdot WBD_{in.air} \cdot (1 - exp(-1.5 \cdot H)) \cdot (1 - exp(-0.15 \cdot WF))) \tag{8.5}$$

The same study mentioned before suggested that the equation with the highest statistical relevance is Eq. (8.1) for all PDEC cases considered (cool, shower/misting tower), followed by Eq. (8.5) for shower/misting towers.

By knowing the inlet and outlet temperatures and the inlet humidity, it is possible to calculate the humidity ratio or the RH of the outlet airflow considering psychrometric expressions for adiabatic cooling transformation—inlet and outlet air have the same WBT. This approach may be followed to check if outlet air RH is out of the comfort boundary, or to define control systems (DEC activation or mixing system coupling treated and external air) to modulate the PDEC functioning. This is especially important during the evaluation of a system's climatic potential, to avoid overestimation of PDEC applicability—e.g. see the specific calculation approach described in [36].

Additionally, dedicated models to simulate DEC systems have been developed for dynamic energy modeling software such as ESP-r [37], TRNSYS [38], DOE2 [39] and EnergyPlus [33].

Finally, there is also specific software devoted to simulating the effect of PDEC towers for architectural design purposes, e.g. [40, 41]. One example is the PHDC Air Flow tool, developed in the 6th EU framework for research and development project 'Passive and Hybrid Downdraught Cooling (PHDC)' [18], which is based on a multizone loop method. The software enables calculation of the air flow generated by the PDEC, the DBT and RH of the outlet air, and the specific flow in PDEC-connected living spaces positioned at different floors. The PDEC systems considered are cool towers (wet pad), shower and misting towers. The obtained values are a function of tower height, the type of wind catcher at the top of the tower (if any), specific nozzle characteristics, the potential presence of an exhaust tower, and floor height and space length (up to four floors can be simulated in the same run in order to check relative results). The distributed version of the software makes a single calculation, based on input data representating internal and environmental starting conditions (outdoor and indoor DBT and RH, wind speed, and height above sea level).

8.2.4 DEC Design Issues

This section investigates some major aspects to be considered in PDEC tower design. First are some of the aspects connected to the evaporative systems, such as nozzle types and bacterial prevention strategies, and these are followed by some of the issues connected to building integration schemes and simple design recommendations.

Main design aspects that may influence the performance of a PDEC tower are related to physical and morpho-technological issues. Considering physical aspects, it is important to remember the wind pressure at the PDEC inlet mount; air specific weight, which varies during evaporation, and motion transfer. Morphological and technological aspects include tower geometry (e.g. height and cross-section area), aerodynamic behaviour of the system, water flow (l/min and distribution), sprayer types, and sprayer numbers and their geometrical distribution—see also [17, 30, 42, 43].

Firstly, as was mentioned in Sect. 11.2.2, it is evident that the choice of the nozzle type is an essential aspect to be considered in PDEC tower design. Research by Guetta [44] compared different available types of nozzle, and as expected, a higher working pressure increased the required power of the pump—it but also decreased the water drop diameter and surface area as well as the volumetric flow rate. Of course fine nozzles show a higher risk of clogging, even if smaller drops may help reduce the time for fully evaporating the sprayed water in the tower system. Conversely, if full evaporation is not needed the system may work at lower pressure with larger drops, reducing maintenance and operational costs. A summary report of these outputs was also included in [1].

In addition, since various types of nozzles are present on the market, especially for pressurized water flow using pumps, the following spray characteristics should be analysed—see also [23, 45].

- The spray angle, which expresses the coverage area considering the tower height;
- The type of cone (e.g. full cone, semi-full cone, hollow cone, flat spray, or air atomizing);
- The nozzle shape (e.g. round, squared, rectangular);
- The number of orifices for single nozzle (e.g. single, multiple);
- The operation pressure at the inlet of the sprayer (e.g. from water district pressure, to high pressure industrial systems);
- The water flow rate at the chosen pressure;
- The size of water drops for a fixed water flow and pressure;
- If given, the Sauter diameter of water drops (D_{32}—see [1]);
- If given, the total surface area of sprayed drops per second;
- The characteristics of the adopted nozzle technology, including pressure, turbulence, and deflection (such as in spiral nozzles) or atomization (by combining water with compressed air).

A second aspect to be taken into account is the risk of microorganism formation (e.g. bacteria, fungi and algae) in the water, especially for preventing legionellosis [46]—see also ANSI/ASHRAE Standard 188-2018 [47]. This is one of the major potential hazards in PDEC system operation, especially where water is not fully evaporated [48]. Several standards and codes of practice include specific aspects to control and prevent the risk for Legionella, especially for large cooling towers in evaporative chillers [49]. A number of specific considerations are especially relevant for PDEC system design. Firstly, water temperature has to be carefully controlled in order to prevent bacteria formation, which principally occurs above 20 °C and below 60 °C—for Legionella the risky domain is 20–45 °C [50]. Secondly, the use of biocides is a highly recommended strategy, especially in combination with water filtering to reduce the presence of potential nutrition particles [51, 52]. Thirdly, the nozzle spray angle may be determined so as to minimize the amount of non-evaporated water reaching the internal surfaces of the PDEC tower and the bottom area outside the collection basin [1]. Fourthly, the usage of drift eliminators is suggested to reduce the amount of water drops remaining in the treated airflow when directed to living space [52]. Furthermore, when PDEC systems are directly spraying in a living space, e.g. in atrium zones, people have to be protected from direct exposure to excessive water spray.

Considering building integration issues, it was demonstrated that between 62 and 82% of existing buildings in southern Europe allow for PDEC system integration [53], for a consequent reduction in cooling energy needs in the range 25–85% [18]. In order to define potential integration schemes, PDEC systems can be classified according to either typology (see Sect. 7.2.2) or building integration mode. Four main integration classes were suggested by Ford et al. [18] in accordance with the position of the PDEC tower relative to buildings and open spaces. Figure 8.9 illustrates these integration modes (see also [54]) that can be defined as: i. attached PDEC tower, such as in the Council House 2 in Melbourne, Australia; ii. detached/isolated PDEC tower, in which the tower has an independent structure and is connected to living spaces by ducts, e.g. Hyderabad centre C II, India; iii. internal closed tower, in which the tower is centrally located in relation to internal spaces, and the system is closed and connected by dampers or other openings to the cooled spaces, e.g. the Torrent research centre at Ahmedabad, India; iv. Internal open tower, in which the PDEC system is integrated in the building, e.g. in an atrium, and directly connected with cooled spaces. In the latter case, dedicated spaces for the collection of un-evaporated water have to be taken into account in the design of the system.

A simplified approach to PDEC integration was recently reported in [26] including a typological table that combines PDEC classes with typical building typologies (i.e. isolated, terraced, courtyard, tower, and linear buildings). The main aspects to be considered for PDEC integration are related to technological and operational concerns, such as the need to avoid the exposure of people and living space to unevaporated water flows, and to architectural concerns such as the visual and aesthetic harmony with existing or newly designed surroundings. In particular, for a central open system, it is suggested to either use cool towers or misting systems or to consider shower towers if a sufficient part of the space is available as a water collecting basin. In this sense, an open tower may be useful in a large building with public open spaces, while in a single building its application is limited in terms of required space

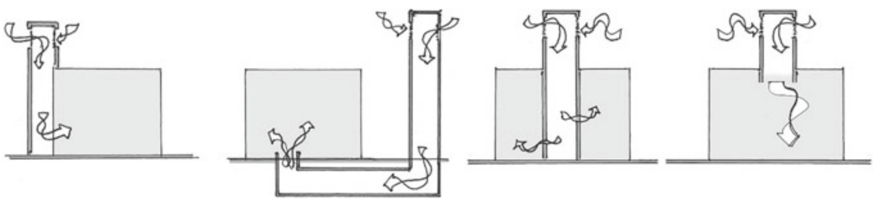


Fig. 8.9 Sample schemes of PDEC tower integration in buildings

and aesthetic impact. For multi-storey residential buildings, attached systems may result in easier integration, even if detached solutions (more useful for tertiary and public buildings, considering the possibility to integrate the system with the existing mechanical ventilation system) or central closed towers may also be considered if, for example, a cavedium (a small atrium to allow ventilation) is present.

Considering tower early-design dimensioning, a simplified approach may be defined, considering the following steps [26]:

- Definition of the airflow rate, which is the higher of two possible values: (1) the rate required for IAQ purposes, based on standard recommendations (see also [55]), and (2) the rate required for cooling purposes, considering the thermal heat to be dissipated and the expected primary airflow temperature. For ventilation, see the simplified formula reported in [56, 57] (Eq. 8.6), that can be adapted for PDEC system by considering the treated airflow temperature, calculated according to the equations reported in Sect. 11.2.3:

$$q_{need-cool} = H/(c_{air}\rho_{air}(\vartheta_{in} - \vartheta_{amb})) \tag{8.6}$$

where H represents hourly heat gains of the space to be cooled on a daily average, c_{air} and ρ_{air} are respectively the heat capacity and density of air, and ϑ_{in} and ϑ_{amb} are the daily average internal and environmental (or PDEC treated) air temperatures.

- Calculation of the minimal required PDEC section area to dimension the tower system, e.g. by using the following (Eq. 8.7):

$$A_{min-PDEC} = q_{need}/C_d\sqrt{\left(\vartheta_{comf} + 273\right)/(\Delta\vartheta \cdot g \cdot h)} \tag{8.7}$$

  where C_d is the PDEC tower discharge coefficient, ϑ_{comf} the target comfort, $\Delta\vartheta$ the average difference between the inlet and treated air temperatures, g is gravitational acceleration and h the tower height.
- Definition of the minimal section area of the opening connecting the PDEC tower with living spaces, e.g. by adopting Eq. (8.8):

$$A_{op} = q_{need}/(C_d \cdot v) \tag{8.8}$$

  where the discharge coefficient C_d refers to the connecting opening, and v is the airflow velocity.

Of course advanced calculations are needed for large installations and detailed design stages. In any case, the potential of a PDEC system for increasing the ventilative cooling applicability is connected to the reduction of the airflow temperature, when the airstream remains in the RH comfort boundaries, for higher heat gain dissipation potential.

8.2.5 Local Climatic Potential of PDEC

DEC systems, such as the majority of passive cooling solutions, show a local specific applicability [58, 59]. This section briefly reports some of the indices available for quantifying this applicability together with an application of some of them to define the geo-climatic potential of PDEC solutions in the extended Mediterranean Basin area.

As mentioned above in Sect. 7.2.4, DEC applicability is related to specific morpho-technological aspects and design choices related to the installed PDEC system. However, even before any design decisions are taken the local potential of DEC is limited by the geo-climatic conditions, since it is a function of the wet-bulb depression (WBD), with the wet-bulb temperature (WBT) representing the theoretical minimal temperature that can be reached by adiabatic cooling alone (Sect. 7.2.1). Different methodologies have been developed to analyse this local climatic DEC potential, including tools and KPIs (Key Performance Indicators). Among such tools is the Ventilative Cooling Potential Tool, which was recently developed under the IEA EBC Annex 62. This application calculates the balance heating temperature of a space unit in a given location and furthermore defines the number of hours in which ventilative cooling is supporting comfort conditions together with the number of additional comfort hours due to DEC operation when the environmental air is above the thermal balance threshold [60, 61]. Among KPIs, a priority classification ranging from Very Low to Very High combines the average seasonal WBD and the average seasonal difference between ambient air and the comfort threshold (e.g. 25 °C or 26 °C) considering cooling hours. This approach was described in [62, 63] and recently was applied to generate a priority map in U.S. [64], while was compared to other approaches considering China locations [36] around the Mediterranean Region [65, 66]. Nevertheless, in addition to averaging indicators, other approaches have been introduced in literature, considering for example cumulative indicators, based on hourly or sub-hourly analyses. One of these approaches focuses on the expected reduction in climatic cooling energy needs, by calculating the residual amount of cooling degree hours (CDH_{res}) in comparison to the environmental (no DEC) amount of CDH in the same location—see also [23, 67, 68]. This approach allows one to consider the virtual effect of a PDEC system in treating the air and consequently reduce the cooling needs by heat gain dissipation. The well-known cooling degree hour (CDH) index, a daily version of CDD (Cooling Degree Day), is based on Eq. (8.9), in compliance with ISO 15927-6:2007 [69]:

$$CDH = \sum_{h=1}^{n} \left\{ \begin{array}{cc} \vartheta_{amb,h} - \vartheta_{tr} & \Rightarrow \vartheta_{amb,h} > \vartheta_{tr} \\ 0 & \Rightarrow \vartheta_{amb,h} \leq \vartheta_{tr} \end{array} \right\} \quad (8.9)$$

where n is the number of hours (h) in the analysed period (e.g. from June to August or, considering the extended summer season from May to October); $\vartheta_{amb,h}$ is the ambient temperature of hour h; and ϑ_{tr} is the calculation threshold. This last value can be calculated as the balance temperature above which it is needed to cool a specific space, or assuming standard values such as 26 °C [70], 25 °C [62], 22 °C [71], 18.3 °C [72] or 15.5 °C [73]. The CDH_{res} index combines the calculation of the expected PDEC treated temperature with the equations reported in Sect. 7.2.3, considering a virtual tower activation when the environmental CDH is higher than zero [68].

This geo-climatic index was compared with results of dynamic energy simulations using EnergyPlus considering a large set of locations (60) in the Mediterranean Region and a large number of design and operational variations for sensitivity analysis (night ventilation, wall insulation level, internal heat gains, thermal mass, roof insulation and window orientation) [66]. Results showed a very good correspondence between the simulated effect of DEC in reducing the indoor discomfort intensity in comparison to the cases without DEC, when analysed using the CIDH index (Cooling Internal Degree Hour, which is an adaptation of CDH for internal conditions) and the reduction of the environmental CDH due to DEC (CDH_{res}). The coefficient of correlation between CDH and CIDH was demonstrated to be quite high ($R^2 = 0.956$ without DEC and $R^2 = 0.903$ with DEC), confirming the significance of the indices used. Secondly, the R^2 value when internal and climatic reduction of the original CDH due to DEC were compared (climate CDH-CDH_{res} vs. building $CIDH_{noDEC}$-$CIDH_{DEC}$) was found to be 0.953, demonstrating the high correlation level between the climatic CDH_{res} approach and the related building conditions. This analysis suggests that the most statistically representative DEC effectiveness for CDH_{res} analyses is 0.6.

Another hourly approach to define the local geo-climatic applicability of DEC is the effect that a PDEC tower is expected to have on the number of discomfort hours for free-running buildings. In this case, the reference number of climatic discomfort hours is compared to that expected when DEC systems are activated. The DEC effect can be estimated by using one of the expressions reported above in Sect. 7.2.3, while the comfort-hour threshold can be defined by using temperature-based indicators (e.g. fixed or adaptive thresholds) or comfort boundaries including temperature and humidity, such as in well-known bioclimatic approaches (e.g. Givoni-Milne [14, 15] or Olgyay [74]). Recently, a comparison similar to the one conducted for CDH_{res} was performed by analysing the DEC effect on the number of discomfort hours of a free-running office building, with and without DEC, simulated in EnergyPlus, and the corresponding number of discomfort hours at the geo-climatic level (before any building definition), with or without DEC [66]. The comfort boundaries were assumed by ASHRAE 55-1992—see also [65] and its representation in Fig. 8.10.

This study shows a very good correlation between the simulated building conditions and the geo-climatic KPI. The highest DEC effectiveness in terms of the discomfort-hour index was demonstrated to be in the 0.6–0.8 domain. Firstly, the correlation between building discomfort hours plotted as a function of climate discomfort hours had an R^2 of 0.924 without DEC and 0.917 with DEC (effectiveness = 0.6), and of 0.896 for a DEC effectiveness of 0.8. Secondly, the percentage reduction in discomfort hours due to DEC in buildings plotted as function of the climate results shows an R^2 of 0.749 for DEC effectiveness 0.8 and 0.790 for an effectiveness 0.6 [66].

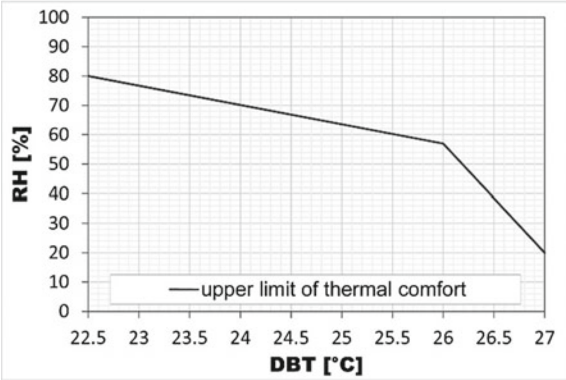


Fig. 8.10 The adapted ASHRAE upper comfort boundary for defining the number of discomfort hours

In order to underline the importance of studying the local potential of DEC, an application of two KPIs (CDH_{res} and the number of discomfort hours) is presented here. A total of 100 locations were selected in the extended Mediterranean Region and their TMY (Typical Meteorological Year) climate data files were generated using Meteonorm 7.11 [75]. The map in Fig. 8.11 plots the selected set of locations. In terms of the Köppen-Geiger climate zone classification [76], the chosen locations include zones Bw, Bs, Cf and Cs.

A reference threshold temperature of 25 °C was assumed for the calculation of CDH and CDH_{res}, assuming a precautionary PDEC effectiveness of 0.6 and using Eq. (8.1) to estimate the PDEC treated air conditions in an extended summer period

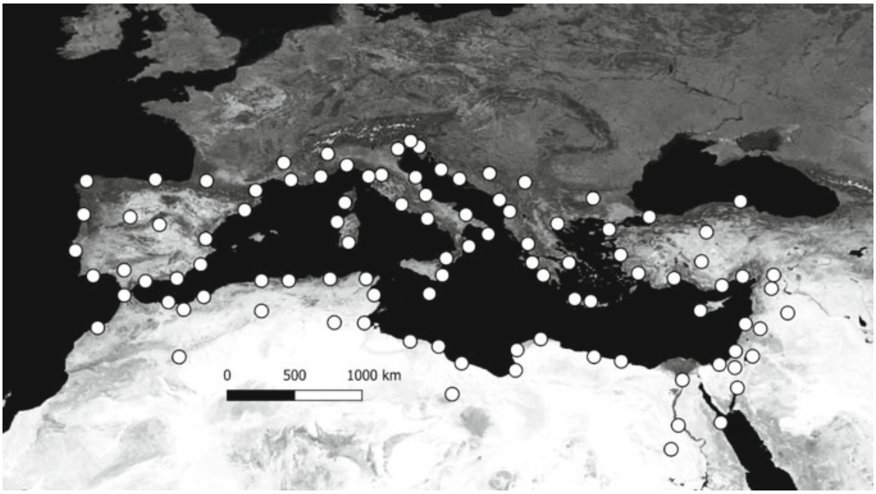


Fig. 8.11 The chosen set of location

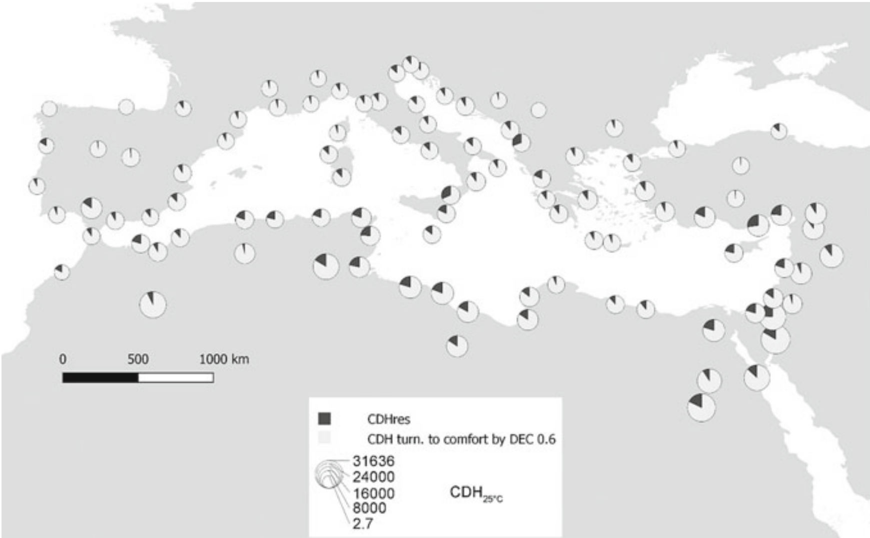


Fig. 8.12 Georeferenced distribution of the reduction in CDH due to DEC for the 100 considered locations. Area of pie charts are proportional to the original CDH, which varies from 2.7 to 31636

(from May to October). Based on calculations performed using a customized tool developed in Python [77], the map in Fig. 8.12 plots the geo-climatic applicability of DEC in reducing the climatic cooling needed in the Mediterranean Region. This map shows that while the general distribution of environmental CDH follows a trend related to latitude (with the exception of semi-mountainous locations), the potential of PDEC for reducing the local climatic cooling requirement is locally specific—see for example the difference between Messina and Syracuse in Sicily, or between the Algerian locations on the coast and in the desert. In general, however, the map shows that PDEC has a very high potential for reducing the original CDH values (as represented by the grey section of the pie charts). As expected, the highest potentialities are prominent in drier locations, such as in central Spain and the semi-desert areas of the Eastern Mediterranean—though PDEC applicability is also quite high in the coastal Mediterranean areas defined as Csa and Csb.

Furthermore, the same set of locations was analysed for discomfort hours both with and without DEC activation, adopting the comfort boundary shown in Fig. 8.10. Also in this case Eq. (8.1) was used to estimate the treated air temperature by a PDEC tower assuming the same precautionary effectiveness of 0.6. The relative humidity of the treated airflow was calculated considering psychrometric equations correlating the vapour pressure (Pv) and the saturated vapour pressure (Pvs) of the treated air. CETIAT tables were assumed to calculate the Pvs, while the Pv is function of the Pvs at WBT, the total pressure, the WBD and the psychrometric constant (0.000662). Results are shown in Fig. 8.13. This map classifies the 4416 seasonal hours in the

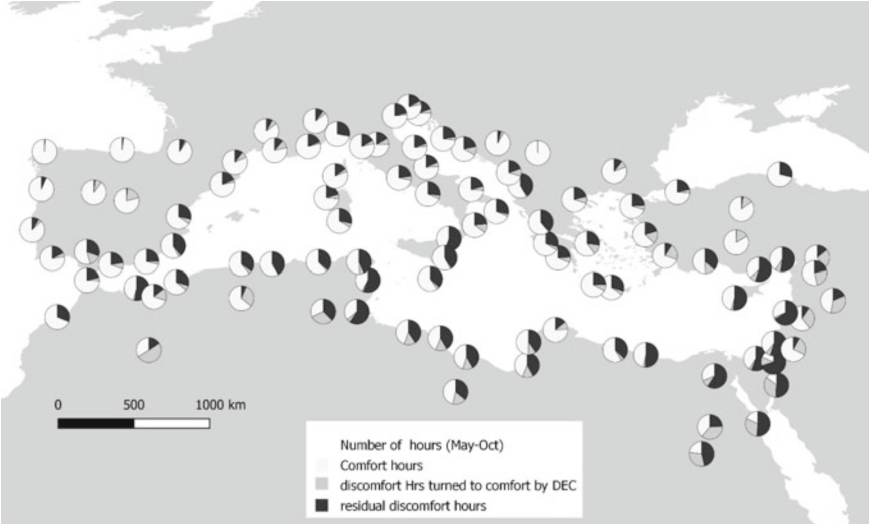


Fig. 8.13 Georeferenced distribution of the reduction in number of discomfort hours due to DEC for the 100 considered locations

extended summer period according to the relative proportion of hours with pre-existing climatic comfort, comfort only after application of PDEC, and residual discomfort even after a PDEC treatment. This breakdown is especially instructive for quantifying the increased potential of ventilative cooling due to a DEC pre-treatment under free-running conditions. The map highlights the fact that higher PDEC potentials are reached in: (i) dry and semi-desert areas, (ii) southern Mediterranean locations, with special regard to central areas such as in Libya, (iii) locations in central Spain, and iv) around the Aegean Sea.

The last two maps and Fig. 8.14 illustrate the extent to which DEC applicability is locally specific, reinforcing the findings of previous studies on the topic (e.g. [78, 79]). Nevertheless, either by adopting available maps or by using devoted KPIs, it is

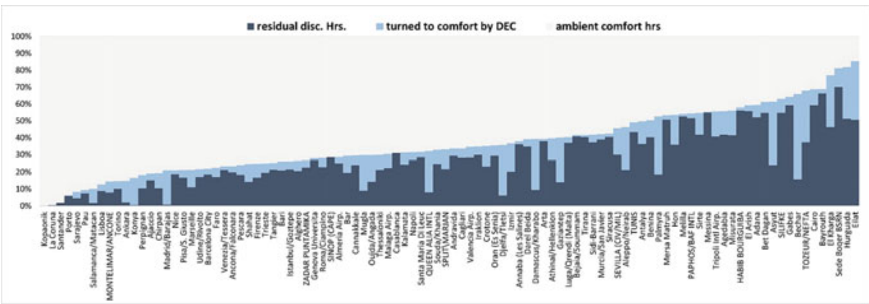


Fig. 8.14 Distribution of comfort hours, residual discomfort hours and ambient comfort hours turned to comfort for the considered set of locations

possible to estimate this geo-climatic potential even in the early stages of building design, and to decide whether PDEC systems represent a valid solution for the particular climatic location. If so, such solutions may significantly boost the ventilative cooling effect and its local applicability when external air temperature and humidity are above the critical comfort threshold.

8.3 Conclusions

This chapter describes basic physical and functional aspects of direct evaporative cooling systems, including different calculation models, and a method to define the climatic local potential of this low-energy ventilative cooling solution. Moreover, a potential applicability map was produced for the Mediterranean basin, based on 100 locations.

Additionally, early-design DEC issues are discussed, suggesting a simple approach for early dimensioning those systems including simple building integration schemes. The adoption of graphical representation tools, such as the Givoni chart, allows to make this approach feasible for both bioclimatic designers and engineers.

On the general point of view, this chapter underlines that DEC systems are valid solutions to increase the applicability and the cooling potential of ventilative cooling systems when ambient temperature conditions are hot and sufficiently dry. Nevertheless, the applicability of these systems requires continuous evaluation and maintenance in order to prevent the potential growth of bacteria and moulds.

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Chapter 9
Ventilative Cooling in Combination with Other Natural Cooling Solutions: Earth-to-Air Heat Exchangers—EAHX

Giacomo Chiesa

Abstract This chapter focuses on the potential combination of ventilative cooling solutions with ventilative ground cooling systems. Horizontal low-enthalpy buried pipes which use air as heat fluid, for example, earth-to-air heat exchangers (EAHX), are focused on in particular. EAHXs may reduce energy consumption for space heating and cooling thanks to their potential to pre-heat and cool an airflow. This chapter describes this technique and includes design suggestions for the application of EAHX in buildings. This solution may be coupled with mechanical VC systems, or be used in naturally-ventilated buildings with the potential support of a fan system to ensure that sufficient airflow is passing through the buried pipes. Finally, a simulation-based approach to analyse the local potential of EAHX to reduce thermal discomfort in naturally ventilated buildings is introduced, thus providing a method for early-design purposes.

9.1 Introduction

From among an array of low-energy techniques to enlarge the local applicability of ventilative cooling systems when external temperatures are above the inlet air temperature comfort threshold, earth-to-air heat exchangers (EAHX, or EAHE) are regarded s being a valid pre-cooling and pre-heating solution during both the summer and winter seasons. This technique is, in fact, able to expand the applicability hours of ventilative cooling by reducing the environmental air temperature thanks to horizontal buried pipes in summer. Furthermore, EAHX facilitates a reduction in thermal losses due to air exchanges to improve IAQ (Indoor Air Quality) in winter.

The basic functional principle of EAHX focuses on the high thermal capacity of the soil which is able to consistently attenuate and shift (both daily and seasonally) the thermal peaks of the environmental air according to depth and earth thermal capacity. As a rule of thumb, it is possible to affirm that at a depth of 10–15 m, the soil temperature fluctuates slightly around the average yearly environmental temperature.

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See for example Ref. [1]. A more in-depth description of this aspect refers to the calculation of the penetration depth of temperature variations—see [2, 3].

The difference in temperature between the earth and a thermovector fluid, generally water or air, is the foundation stone for thermal exchange in EAHX systems. For ventilative cooling purposes, it is possible to cool an airflow directly by using the earth-to-air heat exchanger technique using one or more horizontal buried pipes to circulate air. This system is generally based on an open loop which treats the fresh inlet air, but may also be used in closed loops recirculating internal air.

This technique has an historical vernacular archetype in the "ventidotti" (wind ducts) or "covoli" of the Vicenza area [4, 5]. These historical methods are based on the artificial extensions of natural grottoes to connect natural underground fresh air paths with lived-in building spaces for space cooling by natural ventilation using manual activation of the "covoli" ducts [6]. These solutions were adopted in several Palladian villas, such as Villa Trento and Villa Eolia (Costoza, Vicenza).

Figure 9.1 shows a schematic representation of a "covoli" system—see also [7]. Recent studies were also conducted on these solutions demonstrating their operational potential by using CFD (computational fluid dynamic) simulations [6].

Like the "ventidotti", EAHX uses buried pipes which are positioned horizontally to pre-treat primary airflows for space thermal control.

This chapter describes the main technological and functional principles and requirements of an EAHX system in Sect. 8.2. Physical aspects and calculation models to simulate the soil temperature at a given depth and the EAHX potential in pre-cooling and pre-heating an airflow are illustrated in Sect. 8.3. A method to estimate the EAHX geo-climatic potential is illustrated in Sect. 8.4 and is discussed with reference to climate changes in Sect. 8.5. Finally, a discussion on EAHX and ventilative cooling correlations is included in Sect. 8.6.

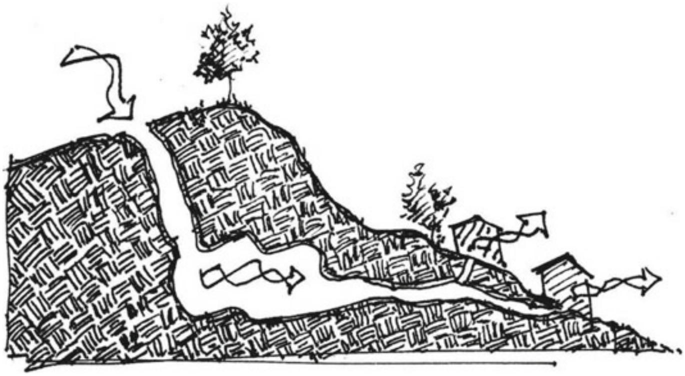

Fig. 9.1 Sample scheme of the vernacular archetype

9.2 EAHX Technological Description

EAHX systems are technologically composed of different sub-parts. Following the airflow, it is hence possible to identify the following technical elements:

1. Inlet caption tower/mouth: a small element in treated concrete or plastic (e.g. PVC) which collects the inlet air and moves it to the ground system. Filters for dust and grids to prevent animals and objects entering are generally included. Furthermore, the inlet air is collected at a height of about 1–2 m to reduce the risk of dust, earth and other contaminants entering the system. Finally, when possible, it is preferable to localize the inlet capture at a summer north-shaded (northern hemisphere) or south-shaded (southern hemisphere) location on the plot to increase the cooling potential by reducing the risk of overheated air at the entrance.
2. Distribution channel (multi-tube system only): a large-section tube used to distribute the collected air into multi-parallel buried pipes which are positioned perpendicularly to the distribution channel length. The connection between the distribution channel and tubes has to be correctly designed in order to reduce friction losses (e.g. by using curved joints). If an inspection chamber is positioned between the inlet caption and the distribution channel to guarantee system maintenance, the distribution tube may be of a diameter which allows for worker inspection.
3. Parallel buried-pipe(s): one or a series of parallel buried pipes acting as heat exchangers between soil and air. This technical element is the main functional section of the system. EAHX performances are mainly correlated to design choices for this specific element, in consideration of diameter, length, depth, positioning and materials. Tube diameter is generally chosen in the range 25–35 cm to balance pressure drops and good heat exchange between air and tube surfaces. Tube length is preferably in the 50–70 m range, even though most heat exchange has been proved to take place in the first 25 m [8, 9]. Tube depth influences the effectiveness of the system as does the risk of summer condensation. Buried pipes need to be positioned sufficiently far from heat sources (e.g. district heating systems, climatised building buried spaces), from the ground water level (to prevent infiltration), and from each other. Tube material must be resistant to humidity and allow for sufficient thermal exchange and good transmissivity. Moreover, a treatment to protect from mould and bacteria formation is required.
4. Collection channel (multi-tube system only): the collection chamber is similar to the distribution channel and has the function of collecting the treated air from each parallel buried-tube.
5. Condensation chamber: the main function of a condensation chamber is to allow the drainage of potential condensed water during cooling mode. The condensation chamber is positioned at the end of the collection channel. In order to support a homogenous airflow distribution inside each parallel buried-pipe the condensation chamber is generally on the opposite side to the inlet caption tower,

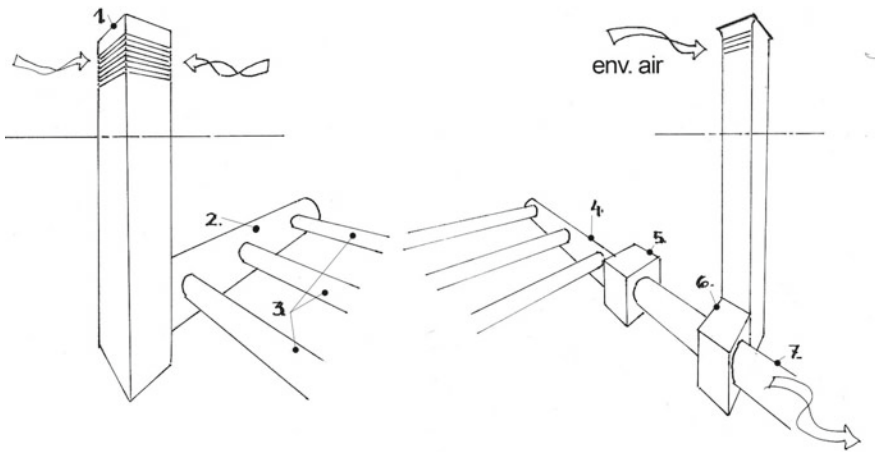

Fig. 9.2 Principal technical elements composing an EAHX system

assuming as reference the length line of buried pipes. In single-tube systems this function may be performed by a small drainage pit, while in multi-tube systems this is generally larger thus allowing for inspection and maintenance.

6. Mixing chamber (multi-field systems): if different multi-tube systems are installed on the same site (multi-fields), the condensation chamber may assume a mixing airflow function or each condensation chamber may be connected to a mixing chamber before building distribution or HVAC connection. This specific technical element is generally the environmental unit in which an external air collector is included to mix treated and environmental airflows when comfort condition falls between the two.
7. Building distribution: building distribution of the treated airflow is generally fan-assisted, even if solar assisted EAHX solutions were presented in Ref. [10, 11] showing good performances. Nevertheless, if the building includes a mechanical ventilation system or a full HVAC, the EAHX is generally directly connected to it and serves as a pre-heating and pre-cooling technique.

Sub-parts 1 and 2 represent the collection section, sub-part 3 is the exchange section, while sub-parts 4, 5, 5 and 7 the distribution section.

Figure 9.2 illustrates a sketch of the mentioned technical elements.

9.3 EAHX Physical Principles

As mentioned above, the EAHX potential in both pre-cooling and pre-heating and airflow is characterised by the earth temperature surrounding the buried pipes. This temperature, if tube influence is not considered, is a function of several aspects including average yearly soil surface temperature, yearly variation of this value, depth, thermal soil characteristics and water level [12, 13]. It is possible to estimate the earth temperature at a given depth in a chosen moment of the year for a specific location by using the Lab [14, 15] or the Hadvig [16] expressions. In particular, the Hadvig formula is reported in Eq. (1):

$$\vartheta_{t,d} = \vartheta_{av} + A \cdot cos\left(\frac{2\pi}{t_0}(t - t_{max}) - d\sqrt{\frac{\pi}{\alpha t_0}}\right) \cdot e^{\left(-d\sqrt{\frac{\pi}{\alpha t_0}}\right)} \tag{9.1}$$

where

t is the calculation time [s] assuming 0 as the beginning of the year;
d is the soil calculation depth [m];
ϑ_{av} is the yearly-average-soil-surface temperature [°C];
A is the annual sinusoidal-amplitude of the soil-surface temperature [°C];
t_0 is the year duration [s];
t_{max} is the moment of the year in which maximum temperature is reached [s];
α is the soil thermal diffusivity [m^2/s].

The surface temperature is a complex parameter to be estimated as a function of several additional factors including air temperature, solar radiation, meteorological conditions, surface covering, long-wave radiation, convective and evaporative transfers [17]. Nevertheless, different approaches were developed in literature to calculate the soil surface temperature at a given moment and the influence of different ground covers on soil temperature profiles—see for example Refs. [18–20]. The yearly-average-soil-surface temperature can be defined from the average air temperature, the long-wave radiation and the mean solar radiation, while the sinusoidal-amplitude refers to the annual oscillations of air temperatures and solar radiation plus the effect of conductive heat transfer. Both parameters may be estimated using the expressions reported in [17].

Specific software may help in defining the parameters needed to calculate eq. (1) which are a function of the soil temperature, i.e. average surface temperature, the phase shift (day of the year in which the minimal temperature is reached—sinusoidally opposite to the maximum one), and the surface temperature amplitude. The CalcSoilSurfTemp program, which is a third party of EnergyPlus [21], can be used to define these parameters by adding the local TMY (Typical Meteorological Year) file, e.g. *.wea, of a location together with soil conditions (Heavy saturated/damp/dry and light dry) and surface conditions (shaded/bare and wet/moist/arid/dry). Even if the program runs the calculation one-location at a time, it is possible to automate the process if multiple locations need to be investigated by adopting a specific script approach—see the R script in Ref. [22], or the Python approach in Ref. [23].

Figure 9.3 shows the soil temperature distribution at different depths (average monthly values) for three types of soil—heavy saturated (α = 9.04E-07 m^2/s), heavy dry (α = 5.16E-07 m^2/s), and light dry (α = 2.8E-07 m^2/s) [24]—in a considered sample location (Turin Caselle, Italy—source: Meteonorm) assuming a bare and moist soil surface condition.

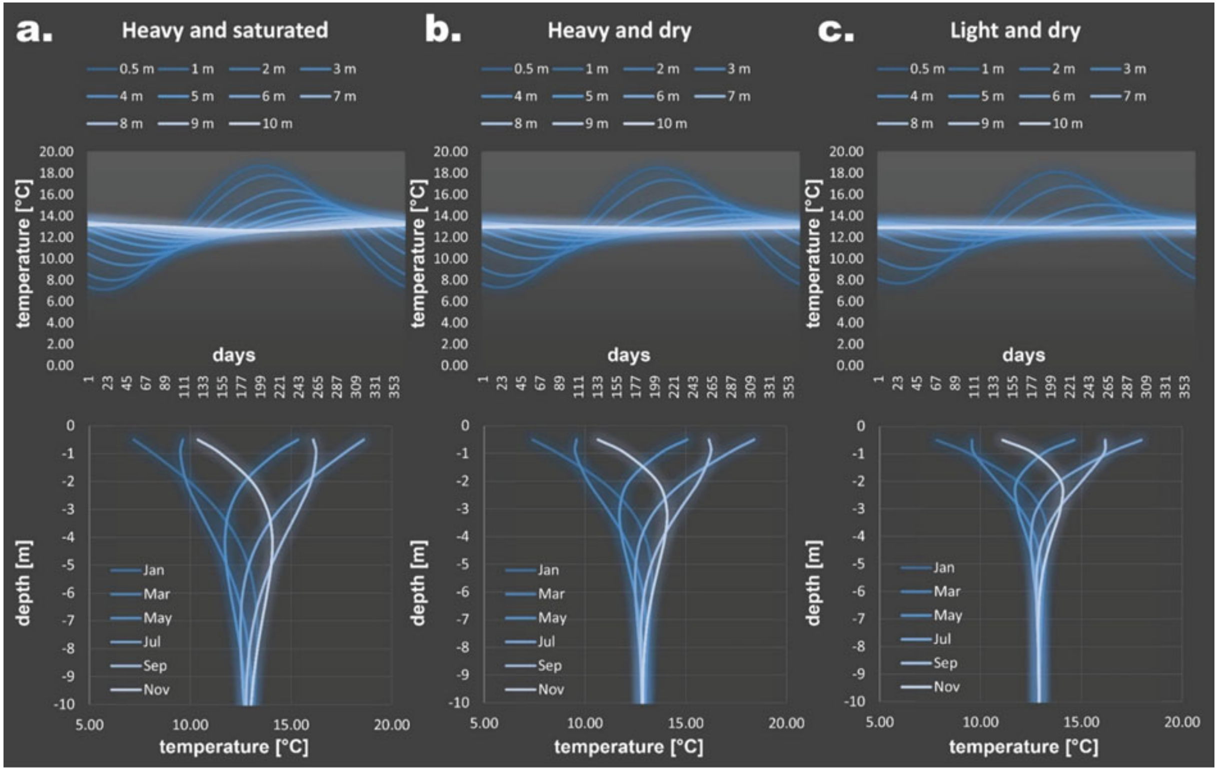

Fig. 9.3 Soil temperature distribution at different depths considering **a** heavy saturated soil; **b** heavy dry soil; and **c** light and dry soil. Top graphs show the daily temperature fluctuations, while the bottom ones illustrate the average monthly distribution of temperature according to depth

When the undisturbed soil temperature at the tube depth is estimated, it is possible to calculate the expected treated airflow temperature from the inlet one, as a function of design choices. Equation (3) was demonstrated to be a valid early-design model for this aim [25].

$$\vartheta_{out,t,EAHX} = \vartheta_{in,t} - \varepsilon\left(\vartheta_{in,t} - \vartheta_{soil,t,d}\right) \tag{9.2}$$

where

$\vartheta_{out,t,EAHX}$ is the temperature of the airflow treated by the EAHX [°C] at moment t;

$\vartheta_{in,t}$ is the temperature of the inlet airflow (e.g. the environmental air temperature) [°C] at moment t;

ε is the EAHX effectiveness [-];

$\vartheta_{soil,t,d}$ is the temperature of the soil at the given depth d at moment t [°C].

The effectiveness of a EAHX is a function of pipe depth, length, diameter, soil characteristics, and airflow rate, which are also the main design parameters which influence EAHX performances—see [26–28]. Different correlations between these parameters and EAHX efficacy were reported in literature—see [2, 22, 23, 29, 30]. For example, Fig. 9.4 reports the average yearly effectiveness value as a function of different EAHX design configurations. These values were calculated by adopting an advanced calculation model—see [25, 31]. The considered location for this example is Palermo, Italy (Palermo/Point Raisi, source: Meteonorm), while the considered variations include air velocity—Fig. 9.4a –, tube diameter—Fig. 9.4b –, tube depth—Fig. 9.4c –, tube length—Fig. 9.4d –, and soil type—Fig. 9.4d.

This figure shows that design choices may considerably influence the effectiveness value. Tube diameter and air velocity have a high impact on this parameter as they are also connected to airflows. Nevertheless, it is important to remember that the effectiveness is only one of the parameters to be considered. It is also important to analyse the airflow requirements, the heat exchange, or the pressure drops of the designed system (and related fan consumptions) to guarantee a high COP.

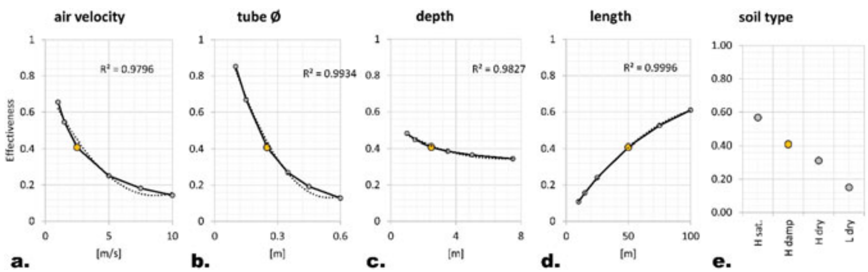

Fig. 9.4 Expected average annual effectiveness of an EAHX system under Palermo climate conditions considering different configurations. Each design parameter changes individually—in yellow the reference assumed value. **a** air velocity variations; **b** tube diameters; **c** tube depths; **d** tube lengths; **e** soil types (H = heavy; L = light)

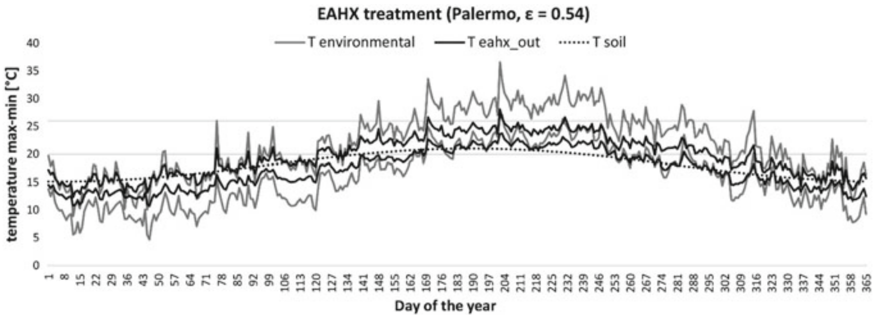

Fig. 9.5 Maximum and minimum air temperature on a daily basis for environmental air, EAHX-treated air, and soil at the buried-pipe level. Horizontal lines represent reference fixed comfort thresholds (20 °C for winter and 26 °C for summer)

Of course this approach is based on average seasonal or yearly effectiveness values and does not include hourly or sub-hourly variations, which may be due, for example, to a variable airflow rate. Nevertheless, this simplified method was validated on experimental data showing good correlations [25]. Otherwise, if advanced calculation models are needed, it is possible to adopt NTU (Net Transfer Unit) approaches—see for example the study in Ref. [32]. Additionally, the software GAEA [33] allows us to perform early-design analysis, while devoted modules were developed for dynamic energy simulation in TRNSYS [34, 35] and EnergyPlus [36]. Finally, advanced CFD simulations were reported in literature [37–39], together with other models [40–42].

Figure 9.5 shows the expected effect of an EAHX considering an effectiveness of 0.54 (0.25 m diameter, 50 m length, 2.5 m depth, 1.5 m/s air velocity, heavy and damp soil) under Palermo, Italy, TMY conditions.

Taking this figure into consideration, the functioning of an EAHX system in pre-treating the primary airflow and its potential to increase the number of hours of applicability of ventilative cooling when external air is over temperature thresholds is clear. Nevertheless, in summer mode, the system may reach condensation or excessive outer air RH% (relative humidity) as it is a sensible cooling technology. If the treated air shows a too high RH% it is possible either to mix the EAHX's airflow with external untreated air or to consider dehumidification treatments.

If we focus on both temperature and relative humidity, Fig. 9.6 shows hourly-averaged results of a monitored EAHX system installed in a school building in Imola, Italy—see [9] –, using a psychometric Carrier's chart. Figure 9.6a illustrates the EHAX effect in a winter month (January) based on hourly averaged monitored data, while Fig. 9.6b reports the EAHX effect in a summer month (July).

The monitored conditions shown in these graphs underline the cooling potential and the high pre-heating effect of EAHXs. These systems can therefore be used alone or in combination with HVAC systems to treat the inlet airflow both in summer (e.g. for IAQ and cooling purposes) and in winter (e.g. for IAQ purposes). As is illustrated by the summer chart, in several hours a potential dehumidification treatment is suggested if the specific final building typology requires RH% control. As regards

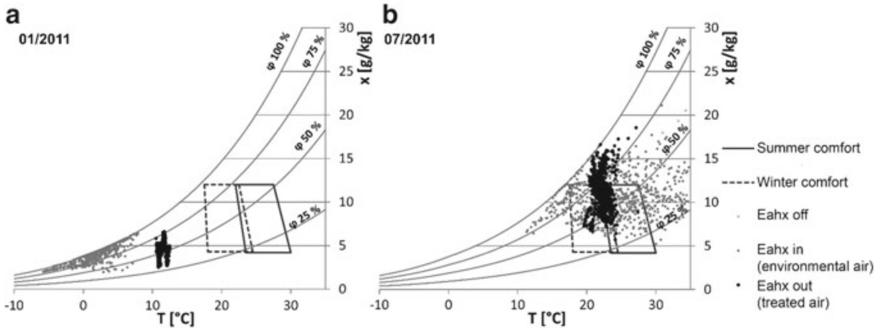

Fig. 9.6 Psychrometric chart representation of **a** monitored data of environmental and EAHX treated air for the month of January, School Building, Imola, Italy; **b** same results for a summer month (July)

EAHX design, simple methodologies for residential and small office installations were reported in literature [2, 5], while another technological and environmental approach was described by the author in Ref. [23].

Additionally, specific monitored case studies were reported in literature including three EAHX systems for tertiary buildings in Germany [43], a residential single tube solution in Northern Italy [44], a residential building solution in Marrakech, Morocco [45], and a review of different experimental installations in Turkey [46],

9.4 EAHX Climatic Applicability

The EAHX potential is directly related to local climate conditions, as was discussed in the previous section. For this reason, the EAHX geo-climatic potential is an essential aspect which must be estimated before conducting advanced simulations to optimise a specific EAHX design. It is also possible to define geo-climatic applicability maps to support incentive policies or help designers to choose the most efficient low-energy ventilative cooling techniques according to location climate conditions.

An approach to define the local geo-climatic potential of EAHX which is compatible with the one illustrated in Chap. 7 for direct evaporative cooling, can be adopted [30, 47, 48]. This method is based on Eq. (2) to estimate the EAHX treated airflow temperature and by comparing this value with the environmental one it is possible to define the reduction in climate KPIs (Key Performance Indicators). The adopted KPIs are the number of potential activation hours while the effect on the CDH (Cooling Degree Hour) index. CDH is a cumulative index of thermal discomfort intensity that can be calculated in accordance with ISO 15927-6. Several studies have demonstrated the direct correlation between this climate index and building cooling-consumption—see for example [49, 50]. Equation (3) reports the adopted CDH calculation expression, where $\vartheta_{env,h}$ is the hourly environmental temperature, e.g. assumed from the local TMY, ϑ_b is the adopted base temperature which corresponds to the balance building-environmental comfort threshold temperature, and *n* is the number of calculation hours (*h*).

$$CDH_{\vartheta_b} = \sum_{h=1}^{n} \begin{bmatrix} 0 & \rightarrow \vartheta_{env,h} \leq \vartheta_b \\ \vartheta_{env,h} - \vartheta_b & \rightarrow \vartheta_{env,h} > \vartheta_b \end{bmatrix} \tag{9.3}$$

In addition to the climate CDH, it is possible to calculate the residual CDH_{res} index, which can be used to analyse the virtual impact of EAHX in treating an airflow. The local potential of this ventilative technique can, in fact, be estimated by using the following expression (4):

$$EAHX_{pot} = \frac{CDH - CDH_{res}}{CDH} \tag{9.4}$$

where

$$CDH_{res_{\vartheta_b}} = \sum_{h=1}^{n} \begin{Bmatrix} 0 & \rightarrow & \vartheta_{env,h} \leq \vartheta_b \vee \vartheta_{out,h,eahx} \leq \vartheta_b \\ \vartheta_{env,h} - \vartheta_b & \rightarrow & \vartheta_{env,h} > \vartheta_b \wedge \vartheta_{out,h,eahx} > \vartheta_b \wedge \vartheta_{out,h,eahx} \geq \vartheta_{env,h} \\ \vartheta_{out,h,eahx} - \vartheta_b & \rightarrow & \vartheta_{env,h} > \vartheta_b \wedge \vartheta_{out,h,eahx} > \vartheta_b \wedge \vartheta_{out,h,eahx} < \vartheta_{env,h} \end{Bmatrix} \tag{9.5}$$

As an example, Fig. 9.7 defines the geo-climatic potential of EAHX in consideration of an effectiveness of 0.59—e.g. a tube installed at 2.5 m in depth, with a diameter of 0.25 m, and an airflow of 250 m^3/h and humid clayey soil [25]—in 100 Mediterranean locations. This calculation was performed using a python code developed by the author, adopting the Metenorm TMY database [51], and the mentioned CalcSoilSurfTemp for filling Eq. (1).

This map shows that EAHX has a very high potentiality in reducing the intensity of the climatic cooling demand in almost all considered locations, with the exception of some very hot sites (e.g. Boqer and El Kharga, South-East area).

Similarly, it is possible to estimate the effect of EAHX on the HDH (Heating Degree Hour) cumulative indicator. Figure 9.8 illustrates the EAHX geo-climatic effect on the original HDH index for each considered location. As is shown in this second map, a limited effect is registered in winter, due, in part, to the higher magnitude of the climatic heating demand intensity. In this last case, the best locations are the worst ones in the cooling-climatic analysis.

Furthermore, the number of potential activation hours of ventilative cooling with and without EAHX is also calculated for the same set of locations. Figure 9.9 shows the obtained results over the whole year and both cooling and heating comfort thresholds (20 °C and 26 °C, respectively). This map illustrates the climatic free-running potential in the set of considered locations. In line with the intensity climatic indexes,

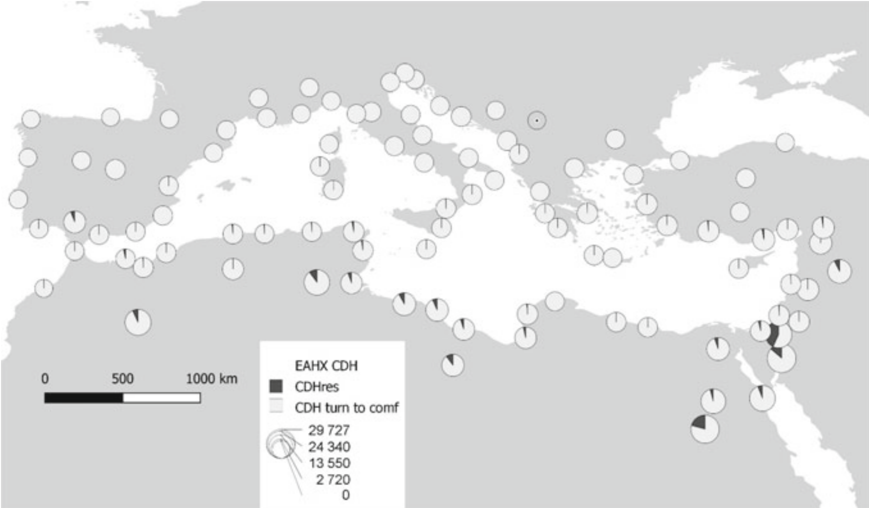

Fig. 9.7 CDH distribution in the considered set of locations and potential reduction of this index due to a virtual EAHX system

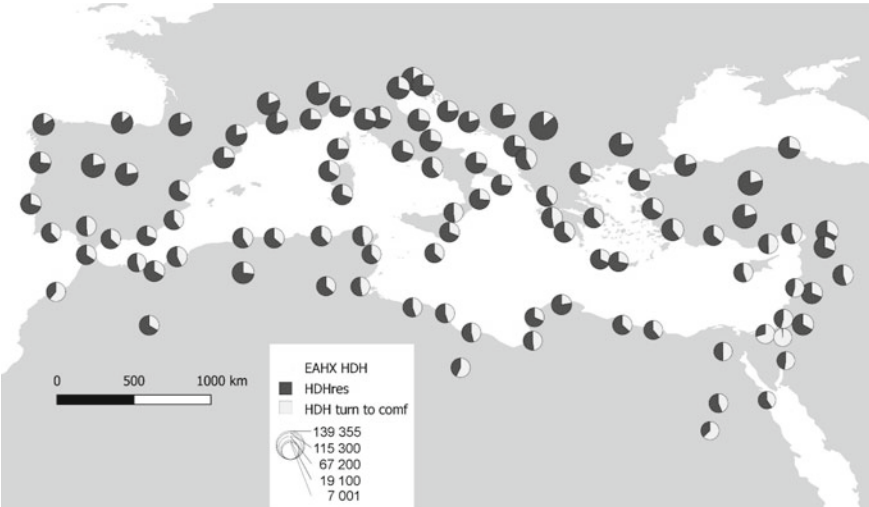

Fig. 9.8 The climatic EAHX effect in reducing the local environmental HDH

the highest EAHX potential is to be found in cooling-driven locations, because the effect on winter-driven climates is not always sufficient to reach comfort conditions. A clear explanation of this result can be derived from Fig. 9.6, considering that, in temperate locations, early average soil temperature at the EAHX depth is generally below the winter comfort threshold—see also Fig. 9.3.

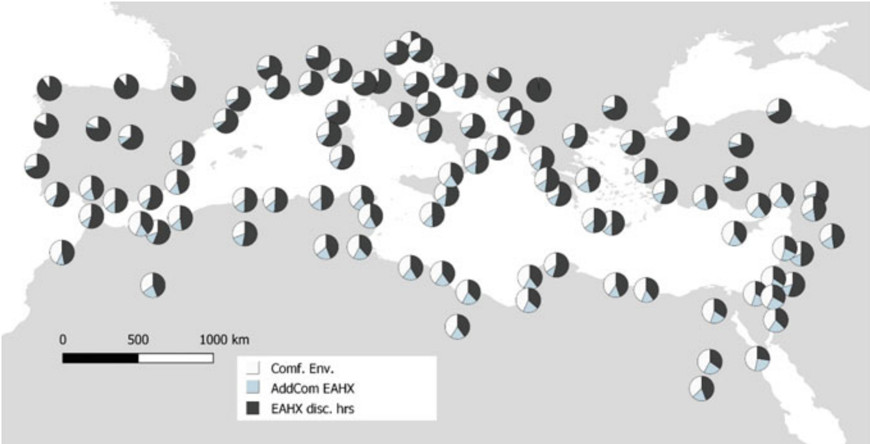

Fig. 9.9 Climatic distribution of the number of environmental comfort hours, discomfort hours transformed to comfort by EAHX, and residual discomfort hours (yearly analysis)

Finally, the climatic potential of EAHX to increase the number of hours in which ventilative cooling may be applied was analysed. In particular, this effect may be defined by calculating the reduction in summer climatic discomfort hours when EAHX is activated. Figure 9.10 reports these values. The map shows that a very high number of additional hours may be expected in central and southern Mediterranean locations. These locations are mainly those in which environmental temperature conditions may exceed, in some summer hours, the comfort threshold, thus

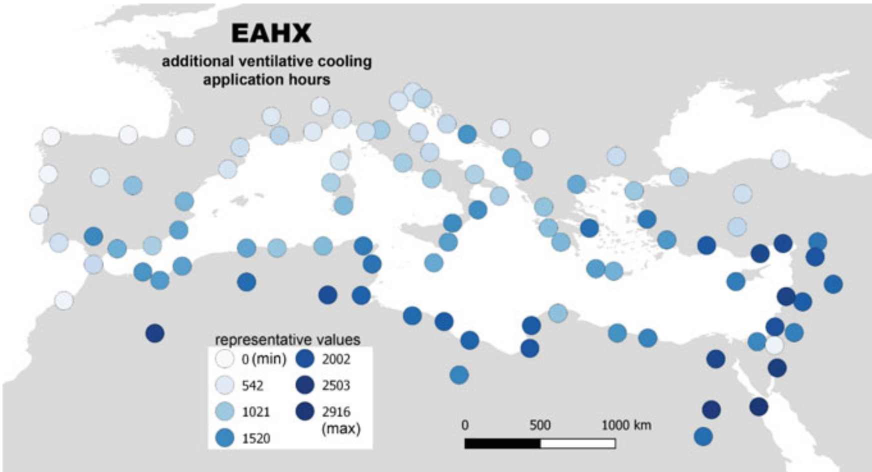

Fig. 9.10 Additional number of hours in which ventilative cooling may be considered when coupled with EAHX systems

reducing the ventilative cooling potential. For this reason, EAHX systems may be valid supporting techniques to increase the area of applicability of this technique.

9.5 EAHX Applicability in Future Climate Scenarios

The proposed approach to define the EAHX geo-climatic applicability allows us to include the estimation of the resilience of this indicator to climate changes. It is, in fact, possible to assume future predicted TMY in accordance with different IPCC scenarios—see for example [52, 53].

A sample calculation of EAHX applicability was performed using the same design inputs as those in Sect. 8.4 in consideration of future predicted climate data. The IPCC scenario A1B (medium scenario, which substantially corresponds to the RCP 6.0 [54]) was adopted and the same 100-location *epw files were produced by using Meteonorm assuming 2050 as the reference year– see the technical manual for additional information about the adopted calculation models [55]. Results were compared with previous ones to analyse the resilience of EAHX applicability.

A general comparison is firstly performed by plotting the calculated parameter which describes the soil surface temperature (average values and amplitudes—max and min). This is defined by processing TMY with the mentioned CalcSoilSurfTemp tool for all locations considering both present and future TMYs. Figure 9.11 shows the obtained results. This graph illustrates a general slight increase in soil surface temperatures—annual average, minimal and maximal sinusoidal values–, even if the effect of the adopted climate scenario is not homogeneous in all locations, as is to be expected.

Secondly, Fig. 9.12 shows the residual HDH (a) and CDH (b) values plotted respectively against climate HDH and climate CDH. In both cases, the graphs show that both the current TMY database and the future predicted one have a similar

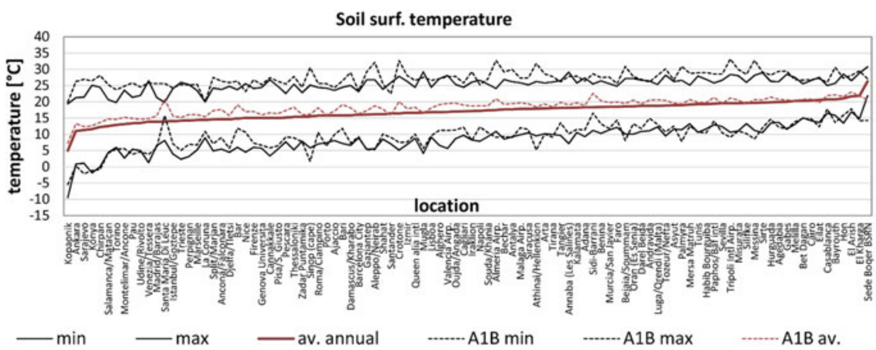

Fig. 9.11 Annual average soil surface temperature, minimum and maximum soil surface temperatures during a yearly sinusoidal period for all considered locations considering current and future-predicted TMYs

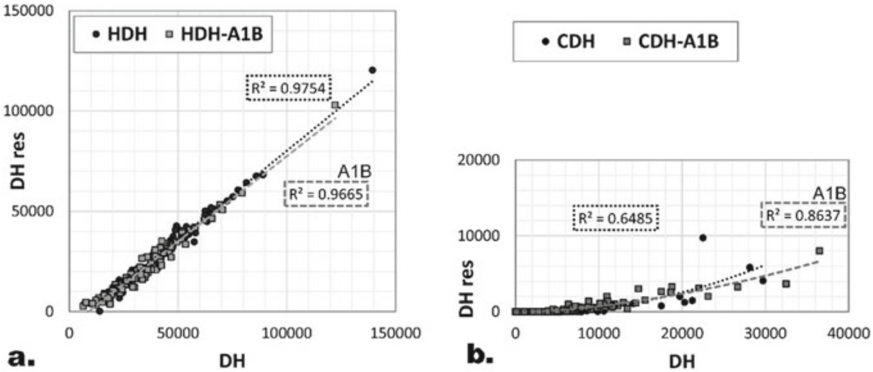

Fig. 9.12 EAHX residual DH plotted against original climate DH in consideration of (**a**) heating and (**b**) cooling indexes. Graphs include both current and future-scenario TMYs

regression curve behaviour. Similarly, the number of residual discomfort hours are plotted against the climate discomfort hours for both heating (Fig. 9.13a) and cooling (Fig. 9.13b). Polynomial regression curves show, also for this indicator, a compatible behaviour between the two databases. From the cooling point of view, a small decrease in EAHX efficacy in turning discomfort hours to comfort is to be found in the central part of the curves, while a higher effect is expected in the upper part (high climate discomfort hours). Nevertheless, this last consideration is based on a limited number of points and requires further investigation.

Thirdly, the relation between current and future DH values—considering both climate and residual data—is analysed in order to verify, in addition to the mutual correlations analysed before, the changes in these parameters. Figure 9.14 illustrates

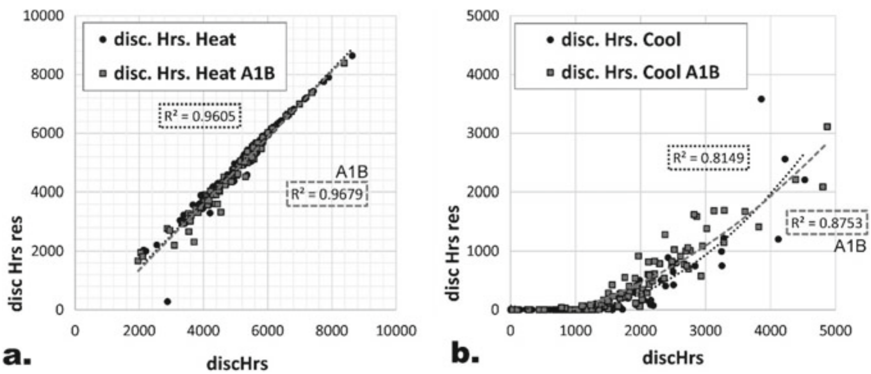

Fig. 9.13 Residual discomfort hours after EAHX plotted against original climate discomfort hours in consideration of both **a** heating and **b** cooling discomforts. Graphs include both current and future-scenario TMYs

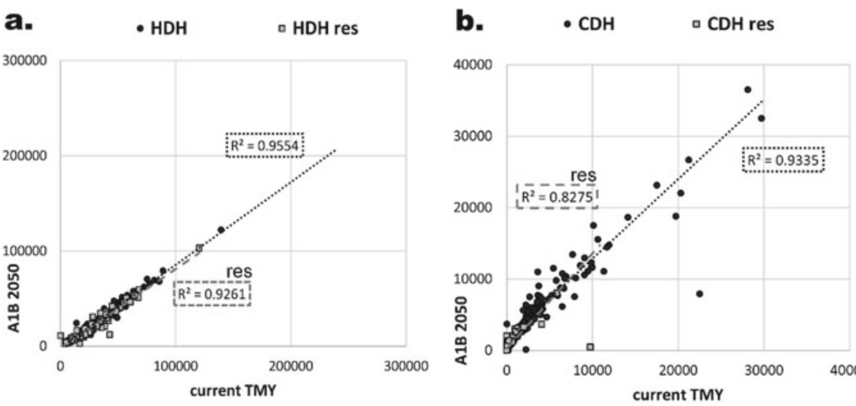

Fig. 9.14 Comparison between current and future-scenario DH indexes considering **a** heating and **b** cooling values

respectively HDH values (a) and CDH values (b) for the considered set of locations. The heating season reveals a general reduction in both HDH and residual HDH indicators when the future climate scenario is assumed. On the other hand, the cooling-season trends, calculated excluding the extreme cases, show an increase in both CDH and residual CDH, but also reflect a slight reduction in EAHX potential, the grey line being above the black one. Similarly, the effects of the climate change scenario on both climate discomfort hours and residual discomfort hours are analysed. Figure 9.15 compares current Vs future databases for numbers of comfort hours during the heating (a) and cooling (b) seasons. A general reduction in winter discomfort hours is evident for both climate and EAHX cases with comparable trends, even if the applicability of EAHX is increased in the A1B scenario if compared to the current

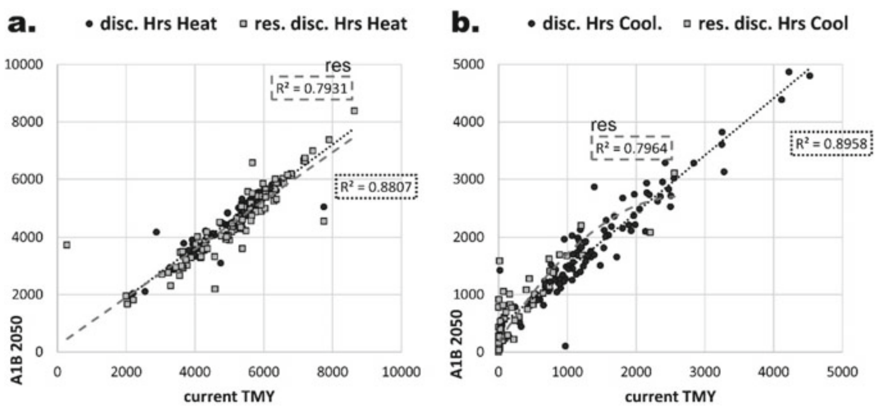

Fig. 9.15 Comparison between current and future-scenario discomfort hour indexes considering **a** heating and **b** cooling values

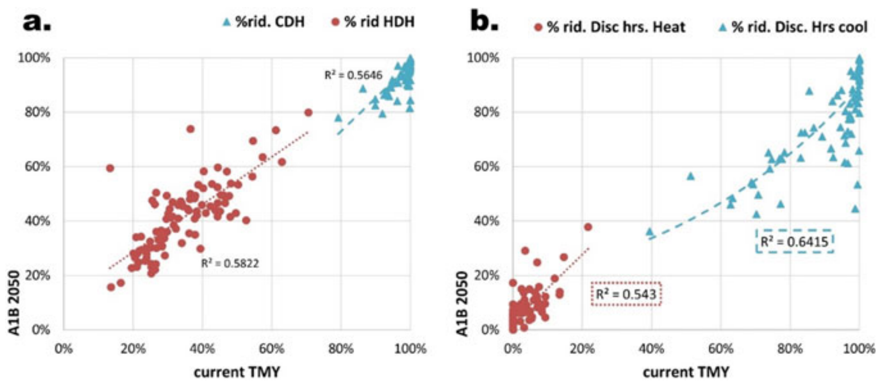

Fig. 9.16 Variations in the EAHX percentage of reduction to climate discomfort due to climate change scenario A1B considering both (**a**) the DH and **b** the discomfort hour indicators

climatic situation. In contrast, in summer, an increase in discomfort hours for both climate and residual calculations is evident, while a slight decrease in EAHX potential in turning discomfort hours to comfort is also shown by the graph. In particular, this reduction is illustrated by trend lines in the domain 500–2000 summer discomfort hours.

The effect of future climate scenarios on EAHX applicability is illustrated by Fig. 9.16. In the heating season, an increase in the EAHX effect in reducing both the discomfort intensity (a) and the number of discomfort hours (b) is evident—see the dotted trend lines. In the summer season, a slight opposite trend is to be seen in these graphs. From the HD point of view (a), the negative impact is limited, as is illustrated by the dashed line. Considering the discomfort hours' indicator (b), a reduction in the percentage effect of EAHX is shown, especially for locations where current potential is very high, a condition that generally corresponds to those locations where cooling needs are very limited compared to heating ones.

These climatic results are in line with general analyses on climate change in temperate and Mediterranean areas and indicate a general increase in average temperatures. Furthermore, the specific regression trends suggest that EAHX behaviour is resilient to climate changes as it both reduces the intensity of climate discomfort and increases the number of climate comfort hours, even if during the cooling season a reduction in its applicability is evident.

Finally, Fig. 9.17 summarises in cumulative frequency graphs the distribution of EAHX outlet and environmental air temperatures in the sample locations of Turin (left) and Palermo (right). The period under consideration is between 1st June to 31st August, while climate data refers to current and future weather by Meteonorm (A1B scenario for 2030, 2050, 2100). The graphs show a constant increase in both environmental and EAHX temperatures in climate change scenarios. Nevertheless, in Turin, the EAHX-treated air is expected not to surpass 26 °C even in typical 2100 conditions. In Palermo, the EAHX effect shows a similar behaviour under climate scenarios with a prevalent sensible thermal translation to hotter temperatures.

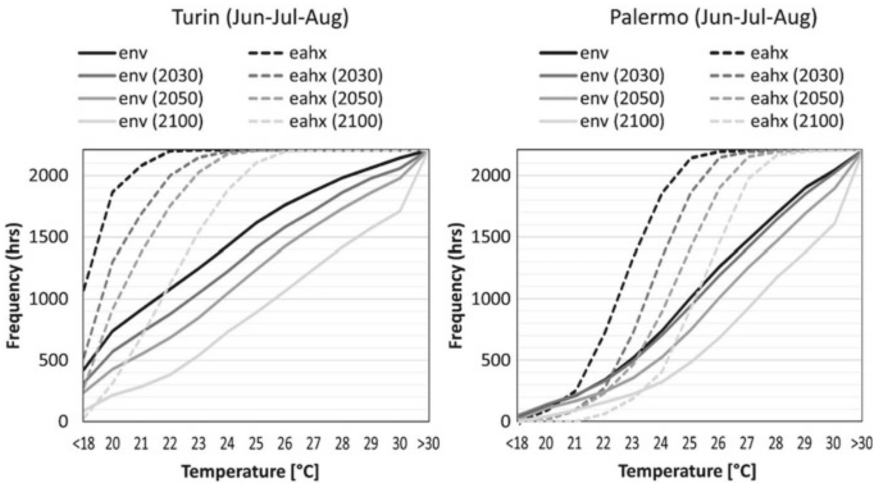

Fig. 9.17 Cumulative hourly frequency of air temperature considering both environmental and EAHX-treated conditions. Current and future TMYs were selected for the cities of Turin (left) and Palermo (right), EAHX effectiveness of 0.59

9.6 Ventilative Cooling and EAHX

The impact of EAHX systems on tventilative cooling focuses on two main issues, as has been suggested in the previous sections:

- Increasing the number of operational hours of ventilative cooling;
- Increasing the impact of ventilative cooling in space cooling.

The practical meaning of the first point is based on those time spams when environmental air temperatures are higher than the comfort/activation threshold for ventilative cooling, requiring for mechanical cooling activation in building spaces, while the temperature of the air treated by the EAHX may reach a condition that allows for space comfort without activating mechanical systems. This specific point refers to free-running conditions, even though the buried-pipe systems generally require a small amount of energy for fan activation. It is possible to represent this issue on comfort charts to graphically describe this principle—see Fig. 9.6.

On the other hand, the EAXH effect on the heat dissipation due to ventilation may be defined starting by the well-known expression (6)—see for example [56]:

$$Q_{vent} = \dot{V}_a \rho_a c_a \left(\vartheta_{air} - \vartheta_{space}\right)[\mathrm{W}] \tag{9.6}$$

where Q_{vent} is the heat flow due to ventilation, $\dot{V}_a$ is the ventilation rate [m^3/s], ρ_a is air density, which can be assumed as 1.2 [kg/m^3], c_a the air thermal capacity, assumed as 1000 [J/kg°C]. ϑ_{space} [°C] is the temperature of the treated space, while ϑ_{air} [°C] is the temperature of the inlet airflow.

The EAHX effect on ventilative cooling is hence obtained thanks to the reduction in the inlet airflow temperature with respect to the environmental temperature during cooling mode. This is principally useful during those hours when the environmental air temperature is not sufficient to guarantee natural ventilation effectiveness and dissipate heat gains. Nevertheless, this may also reduce the amount of ACH (Air changes for hour) needed during the ventilative cooling mode.

To simplify the practical significance of this effect, it is possible to refer to a sample case concerning the calculation of the required amount of ventilation rate to cool a spce by ventilative cooling. This value may be deducted by adapting Eq. (6) to the amount of heat gains to be dissipated [W]—see Eq. (7) [5].

$$\dot{q_a} = \frac{H}{\rho_a c_a \left(\vartheta_{air} - \vartheta_{space}\right)} \frac{1}{3600[s/h]} \left[\mathrm{m}^3/\mathrm{h}\right] \quad (9.7)$$

where H is the average amount of heat gain to be dissipated at hourly base in the space to be cooled by ventilation.

In Torino-Caselle climate conditions, the average monthly environmental air temperature in July (typical summer month) is calculated to be 22.9 °C. The average temperature of a EAHX-treated airflow is 18.5 °C during the same month with an EAHX effectiveness of 0.59 (2.5 m depth, heavy, damp soil). Considering a sample office space with 20 W/m^2 for internal gains and 30 W/m^3 for solar gains [57] and an occupancy type of 8 h, the daily average amount of heat to be dissipated in a 50 m^2 space (room height = 3 m) is 20000 W on a daily basis. Considering an activation time for ventilative cooling of 10 h and a comfort temperature of 26 °C, the required ventilation rates are 0.67 m^3/s and 0.28 m^3/s respectively for the environmental ventilation and the EAHX-assisted ventilation. The first requires 12.86 ACH, and the second only 5.3 ACH. In hotter locations, such as, for example, Palermo, the positive effect of EAHX in supporting low-energy ventilative cooling is even more evident, the average temperature of the environmental air (26.4 °C) being above the assumed comfort threshold and the EAHX-treated air temperature of 23.4. In this case, the percentage of days on which the average temperature is below the comfort one is only 45%, while in the EAHX case this value is 97%. It is evident that EAHX may be a valid solution to support ventilative cooling in several hot Mediterranean locations.

9.7 Conclusions

This chapter introduces EAHX techniques as pre-cooling solutions to enhance local ventilative cooling potential. Technical and early-design issues are reported and basic functional and technical considerations given to help designers to define early-EAHX configurations. Furthermore, the physical principles of EAHX in treating inlet airflows are discussed with regard to both cooling and heating modes. Like several low-energy techniques, EAHXs show local climate-related potential. The chapter introduces two indicators to define this geo-climatic applicability. One hundred Mediterranean basin locations are selected and show that this technology is very effective in both increasing the number of hours for ventilative cooling and reducing cooling-need intensity. Furthermore, this potential has been tested against a medium-impact future climate change scenario and has shown good resilience. Buried pipes are expected to increase their potential in heating mode (pre-heating for HVAC system and/or reducing heat losses for IAQ ventilation flows) and to maintain their positive effect in cooling mode. Nevertheless, a slight decrease in cooling effect is expected in some locations due to the growth in typical local meteorological temperature profiles. A practical significance of the considered analyses is introduced to give consistency to the combination of EAHX with ventilative cooling. This low-cost technique is demonstrated to be a valid solution to increase low-energy ventilative cooling in buildings, in particular in temperate and Mediterranean climates.

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Chapter 10
Ventilative Cooling and Urban Vegetation

Katia Perini and Gabriel Pérez

Abstract The chapter analyses the potential usage of vegetation in cities to provide cooling effect due to plant evapotranspiration, shading and air flow control, discussing how lower temperatures, pressure differences and air flows can favour natural ventilation to improve comfort and reduce energy demand. Due to the urban heat island phenomenon, which is connected with the lack of green areas and the amount of surfaces with low albedo, cities face discomfort issues and higher energy demand for air conditioning. Urban greening, green roofs and vertical greening systems, depending on plant species, material used and climate, can improve environmental quality: at city scale mitigating urban heat island, improving outdoor comfort and providing additional benefits; at building scale, reducing the energy demand for cooling and favouring natural ventilation. In order to deeply address these aspects, the chapter comprises the analysis of case studies and monitoring activities related to urban greening, green roofs and vertical greening systems.

10.1 Urban Greening

Urban features and anthropic activities cause environmental degradation in cities and discomfort conditions. The amount of artificial surfaces with low albedo, car traffic, emissions due to industrial and domestic plants, the lack of green areas, building density, etc. are responsible for poor environmental quality and pollution. The urban heat island phenomenon, i.e. the temperature difference between cities and suburban or rural areas, is determined by the mentioned issues [1]. The phenomenon has been increasing in the past years [2, 3] also due to climate change, with relevant impacts of human health and increase in building energy consumption, especially

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during summer [4]; for example, in Athens, cooling demand doubled due to ambient temperature increase [5]. In addition, air conditioning increases, itself, the Urban Heat Island phenomenon [6], causing an increase up to 2.56 °C in outdoor air temperature [7]. This is an important issue to consider in order to, from one side, reduce the buildings related energy consumption and emissions and, from the other, increase the thermal comfort of cities.

Urban greening can mitigate the urban heat island phenomenon and improve outdoor thermal comfort, as demonstrated by several authors [8–10], thanks to its cooling potential. In addition, vegetation in cities collects fine dusts, resulting in air quality improvement [11], contributes to sustainable water management [12, 13], provides acoustic insulation and noise reduction [14–16] and habitat for biodiversity [17, 18] with social and aesthetics effects [19–21].

In order to obtain the environmental benefits which urban greening can provide, a wide range of green infrastructure can be integrated in dense urban areas. These include: urban parks with different sizes, street trees, domestic gardens, green infrastructure specifically designed to improve water management, as rain gardens and vegetative swale. Vegetation at building scale can also be exploited for ventilative cooling, for the reduction of energy demand for air conditioning, for thermal comfort improvement; for such purpose green roofs and vertical greening systems can be an interesting option, as discussed in the Chapter.

10.2 Greening the Building Envelope

10.2.1 Green Roofs

A green roof is composed of layers that allow establishing and developing vegetation on the top of buildings. From top to bottom, above the structure of the roof, these layers are the vegetation layer, substrate layer, filter layer, drainage layer, protection and water retention layer, and finally the root barrier and waterproofing layer [22]. Although maintaining this basic multi-layer structure, three large groups of green roofs can be clearly differentiated; extensive, semi-intensive and intensive green roofs (Fig. 10.1).

Extensive green roofs are mainly designed to provide aesthetic and ecological benefits, being usually forbidden its pedestrian use. Main characteristics of extensive approach are its low cost, lightweight, minimal maintenance requirements (1–2 times per year) and the use of self-generative plant species. Intensive green roofs look like real “roof gardens” since they are designed and developed as public open spaces to be used as parks and/or building amenities. Thus intensive systems are characterized by higher weight and maintenance as well as intensive planting, ranging from lawns to shrubs and trees. Semi-intensive design try to avoid the extensive approach drawbacks under extreme climate conditions by increasing the thickness of some layers such as substrate and water retention layers, in order to

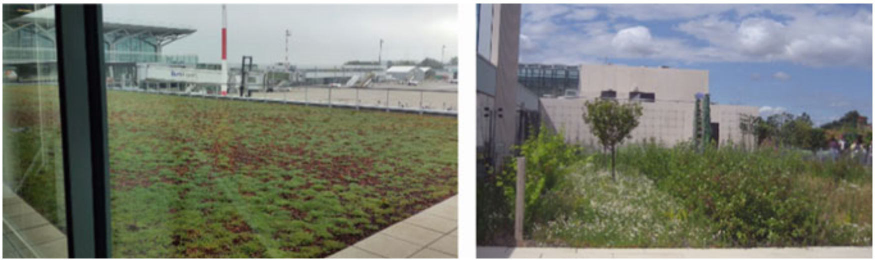

Fig. 10.1 Left: Extensive green roof. Zurich (Switzerland) 2017. Right: Intensive green roof. Greenwich (UK) 2015

Table 10.1 Main green roofs typologies and their characteristics

	Extensive	Semi-intensive	Intensive
Weight at field capacity	50–150 kg/m^2	120–350 kg/m^2	>350 kg/m^2
Substrate layer thickness	6-20 cm	10-25 cm	>25 cm
Plant species	Succulent, herbaceous and grasses	Herbaceous, grasses and shrubs	Grasses, shrubs and trees
Maintenance and irrigation	Low	Moderate	High
Use	Only accessible for maintenance (slope < 100%)	Pedestrian areas but with a moderate use (slope < 20%)	Pedestrian/recreation areas (slope < 5%)

guarantee the plants survival, but consequently the system weight and the required maintenance level are higher. Table 10.1 summarizes the main features of these three typologies of green roof [23, 24].

10.2.2 Vertical Greening Systems

Vertical greening systems are commonly classified as living wall systems and green façade, depending on the growing method and supporting structure used [25–27] (Fig. 10.2). Living wall systems are based on thin panels for the growth of different plant species, including shrubs and climbing plants. In order to provide water and nutrients to plants, an irrigation system is always included in the design of a living wall system and nutrients are periodically supplied. The many systems on the market use different materials for the supporting panels: felt or other textile layers overlapped on top of a waterproofing layer working as support (e.g. PVC panel) to create small pockets for the plants; plastic planter boxes filled with organic substrate, foam panels, etc. Living wall systems must be carefully designed, especially the irrigation system

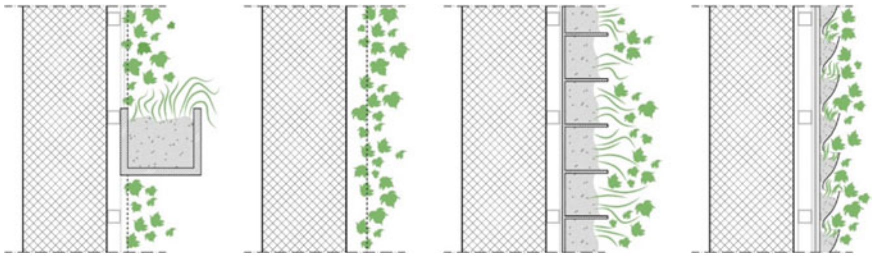

Fig. 10.2 Vertical greening systems: green façades (**a** with planter boxes and **b** indirect) and living wall systems (**c** plastic modular panel and **d** felt layers) [25]

to avoid the death of plants. These systems contribute to the building envelope performances, thanks to the materials involved [28], but entail often higher economic and environmental costs compared to green façades [29, 30].

Green façades are based on climbing plants rooting in front of a building (in the ground) or in planter boxes, placed also at different heights of a building (e.g. on terraces). Plants can be attached directly to the building envelope or to a supporting structure (indirect green façade), made of a steel mesh, wood or plastic structures. Maintenance is usually simple, costs lower as well as environmental impact [29, 30]. The use of supporting structure creates an air cavity, which has thermal benefits for the building envelope [31] and reduce the risk of damage to the façade.

10.3 Operating Methods

The benefits that greenery provides to the urban environment improvement and outdoor comfort, as well as to the passive energy savings in buildings and indoor comfort, are currently well known and reported [32]. The main mechanisms that regulate this set of ecosystem services provided by green roofs and VGS are basically four, the shade effect, the cooling effect, the insulation effect, and finally the wind barrier effect [33] (Table 10.2).

The *shade effect*, which is probably the most significant for the energy savings purpose, consists basically on the solar radiation interception provided by plants.

Table 10.2 Operating methods of urban vegetation for thermal and comfort benefits

Effect	Operating method
Shade	Solar radiation interception provided by plants
Cooling	Evapotranspiration from the plants and substrates
Insulation	Insulation capacity of the different construction system layers: plants, air, substrates, felts, drainage materials, etc.
Wind barrier	Wind effect modification by plants and substrates

The *cooling effect* takes place due to the water evapotranspiration process from the substrates (evaporation) and plants (transpiration). This effect has a double component since while heat energy is removed during the process, the relative humidity increases due to the evapotranspiration process, which implies a refreshment of the adjacent air layer. Ventilative cooling strategies could take advantage of this effect to increase its efficiency by means of the displacement of this fresh air towards areas where the aim is to reduce the temperature and raise relative humidity. In this regard, the water content on the substrate, and its capacity to store water, as well as the plant species used, are key aspects to consider.

The *Insulation effect* is related to the insulation capacity of the different materials used in the solution, especially the substrate and drainage layers, and their thickness.

Finally, the *wind barrier effect* refers to the capacity of green roofs to modify the direct wind effect on the building, either by cooling or by heating it.

Knowing these passive operating methods, it is necessary to look for ways to activate these systems and/or linking them to the ventilative systems in order to exploit all their cooling potential.

10.4 Greening Cities to Improve Environmental Conditions

Green areas in cities allow regulating air temperature, air flow, mean radiant temperature and relative humidity, with effects evident at a range of scales (city, district, canyon scale). In order to exploit the cooling capacity of vegetation, plant species characteristics are important (Table 10.3), as well as the position in relation to the built space. For example, trees planted in urban canyons, roadside or in the middle of a canyon, have different performances in terms of outdoor thermal comfort, since roadside greening reduces wind speed [34]. Plant species characteristics (in particular morphological properties) have different solar attenuation capacity [35]. Lee et al. [8] show that trees mitigate air temperatures up to 3.4 °C, while grassland up to 2.7 °C, mean radiant temperature reduction are respectively 39.1 and 7.5 °C and PET values 17.4 for trees and 4.9 for grassland.

Urban greening reduces high ambient temperatures in built environments, resulting in potential energy savings for cooling [39].

Green courtyards are traditionally used in some areas (e.g. the *patio* of the region of Andalucia, Spain) to favour natural ventilation: pressure difference between cooler and hotter areas increase natural ventilation (Fig. 10.3). When vegetation is planted in a courtyard, i.e. a small area within buildings, the humidity increases due to evapotranspiration, which implies a thermal energy absorption able to mitigate urban temperatures, with most of solar radiation transformed into latent heat [39]. Air flow direction and intensity can be regulated by means of trees and shrubs, and therefore exploited for natural ventilation. In addition, air passing through leaves is cooled by the mentioned mechanism.

Table 10.3 Main characteristics of vegetation affecting outdoor comfort parameters (based on [34, 36–38])

Foliage shape and dimensions • Regarding mean radiant temperature, foliage determines shadow area, depending on the site latitude • Row/group of trees can create a barrier or increase air flow • Foliage affects plants evapotranspiration, which results in reduced air temperatures and increased air humidity
Height of trunk • Regarding mean radiant temperature, trunk's height determines shadow area, depending on the site latitude • In order to protect from winter wind, trunks height should be reduced
Leaf area density (LAD) • High values reduce the solar radiation transmitted during summer. • Leaf Area Density determines the air flow through the foliage (low or high) • LAD affects plants evapotranspiration, which results in reduced air temperatures and increased air humidity
Seasonal cycle • Deciduous plant species avoid winter shading • Evergreen species are required for winter air flow control
Daily transpiration • High levels of daily transpiration cool the air flow passing through trees • Transpiration implies a thermal energy absorption able to decrease summer overheating and increase air humidity

Fig. 10.3 Natural ventilation favoured by a green courtyard

Mean radiant temperature of buildings depends on material properties and therefore is influenced by the presence of green areas, trees, grassland, etc. *[40]. The shading effects of plants result in lower surface temperatures around 1–2* °C *at night and around 4-8* °C *during the daytime [39].*

By means of dynamic simulation, parametric design and genetic algorithms, the optimal position of trees around a 1-floor and a 2-floors building are identified for the city of Rome, to reduce the energy consumption for cooling. Results show that the shading effects of trees have a significant influence with an energy consumption decreases in a range of 11.1–12.8% for a 1-tree configuration, up to 48.5%. for a 5-trees configuration. The study shows also that east and west sides are most favourable positions to reduce energy consumption [41].

10.5 Greening Buildings and Ventilative Cooling to Improve Energy Performances and Thermal Comfort

The cooling capacities of vertical greening systems can be exploited to improve the energy performances of buildings and indoor thermal comfort. Several researches show that vertical greening systems and green roofs can be used as passive tool for energy savings at building scale [42]. The system characteristics highly influence the performances (e.g. green façades vs living wall systems, see par. 9.2.2), as well as plant species density (i.e. leaf area index, LAI), transpiration, etc. *[43], by means of Computational Fluid Dynamics (CFD) simulations, for which vegetation is modelled as porous medium, show that the design has to consider the coverage (block ratio) in order to obtain optimal ventilation performance.*

The shadow effect and evaporation capacities can be effectively exploited during cooling periods to improve indoor thermal comfort, resulting in energy savings for air conditioning and mechanical ventilation. The temperature difference created by a green layer can be exploited to increase natural ventilation (thanks to pressure differences). [44] study the improvements in indoor thermal comfort which can be obtained by adopting water-to-air heat exchangers (WAHE) and indirect evaporative and radiant cooling strategies in buildings with green roofs. According to the authors, future research should experimentally evaluate the system performance with a fan sensor that re-circulates the indoor air through the WAHE or provide natural ventilation as required according to seasonal variations. *In order to discuss these aspects, some case studies are presented.*

10.6 Case Studies and Monitoring Results

10.6.1 INPS Green Façade: A Pilot Project Built in Genoa, Italy

The pilot project and the monitoring activities

The INPS Green façade pilot project (Fig. 10.4) was installed on the south wall of INPS (National Institute of Social Insurance) headquarters in Sestri Ponente, Genoa (Italy) in 2014. The building envelope is exposed to solar radiation 8 h/day in summer and 1–2 h/day during winter and is made of two layers of masonry with a 51 cm air gap and a 5 cm of insulating layer (polystyrene), with a thermal transmittance of 0.44 W/m^{2}K. The geotextile panels of a living wall system cover 120 m^2; climbing plants placed in the panels grow on steel meshes (for additional 35 m^2 of the external

Fig. 10.4 The pilot project INPS Green Façade, Genoa (Italy)

wall). Several shrubs and climbing plants were planted in order to monitor their adaptation capacity and performances. Among these *Rhincosperma jasminoide, Hedera helix, Phlomis fruticose, Cistus Jessami beauty* can be mentioned. An irrigation system provides water and allows the plants survival.

Monitoring activities developed from 2014 to 2018 are focused on the environmental, economic and social benefits of the pilot project. Such monitoring activities include:

- a sociological investigation, implemented before and after construction [45, 46];
- sampling and analysis of leaves (plants: *Rhincosperma jasminoide, Hedera helix, Phlomis fruticose, Cistus Jessami beauty*) to compare the fine dusts collecting capacity [11];
- Field measurements of environmental parameters (air and surface temperature, relative humidity, solar radiation, etc.) to quantify the cooling performances of the system [47, 48];
- Cost benefit analysis to evaluate the economic sustainability of INPS green façade pilot project [49];
- Life cycle assessment to evaluate the environmental sustainability of INPS green façade pilot project (preliminary results in [50]).

A thermographic analysis was performed before and after the installation of the vertical greening system in order to, first of all, highlight the structure of the building and the presence of thermal bridges and, after the installation, the surface temperature difference (Figs. 10.5 and 10.6).

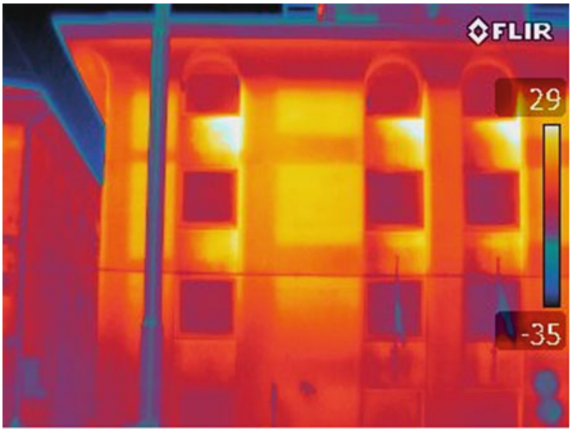

Fig. 10.5 Photo of the facade made with infrared camera before the installation

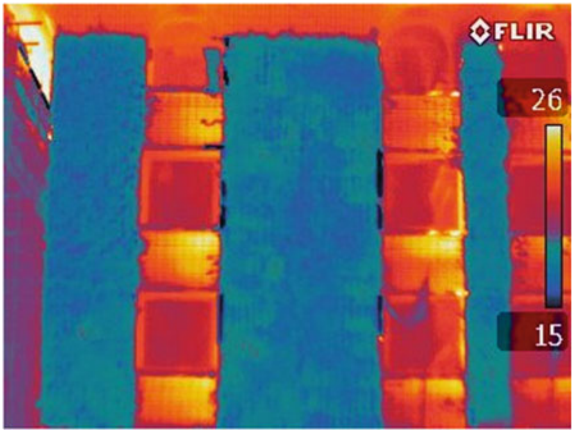

Fig. 10.6 Photo of the INPS Green façade with infrared camera before the installation

Thermal performances

As described previously in the chapter, vertical greening system have interesting performances in terms of cooling potential, which could be exploited for indoor ventilation and air conditioning. The summer monitoring campaign performed on INPS Green Façade focused on such aspects [47, 49]. The main quantities analysed are (Fig. 10.7): external surface temperatures in presence and in absence of the vertical greening system; solar radiation, outdoor air temperature and humidity are also monitored. In order to monitor a potential air temperature difference to be exploited for indoor ventilation and air conditioning, two 8 cm diameter ducts were made throughout the building wall, of which one is below the green layer, provided with a resistance temperature detector. Air is extracted by means of an impeller (Axial fan a.c. 80 x 80 x 25mm, max air flow 41 $m^3 * h^{-1}$) from the gap between the vertical greening system and the external wall and from outside, allowing a continuous comparison between the data recorded.

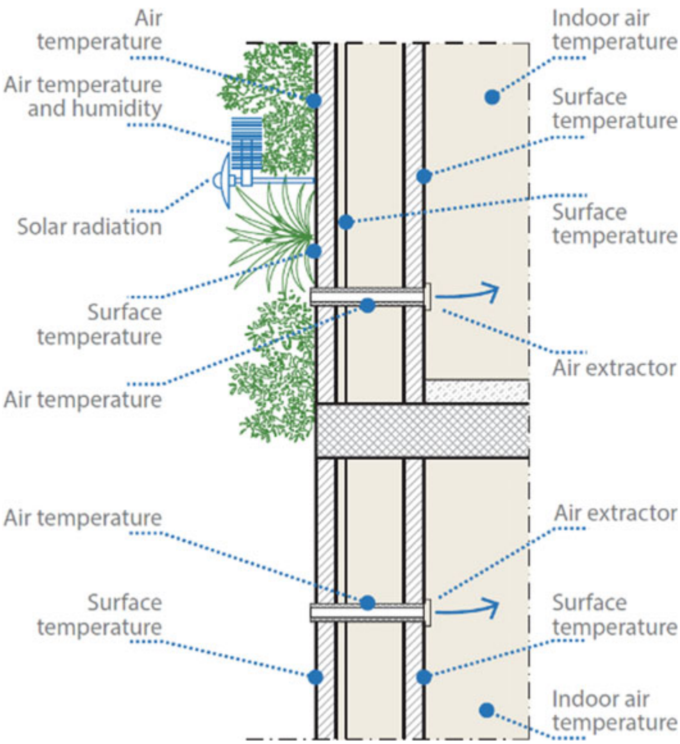

Fig. 10.7 Energy monitoring system [49]

The results of the monitoring campaign, performed during summer 2015-2016-2017 from the 1st June to the 30th September (for 2017 the month of September is not considered), are presented in Table 10.4. The data analysed are related to a public office building occupancy hours i.e. from 8 A.M. to 6 P.M. Data show monthly average air temperature difference between green and no green in a range of 1.5 up to 6 °C. In addition, the monthly number of office hours during which the air with and without the influence of the greening system exceeds 26 °C[1] are measured. Results show that, thanks to the cooling potential of the green layer, the number of hours with Tair > 26 °C is 0 in most of the month, with exception for July and August 2015 (respectively 19 and 6).

The cooling potential of the VGS can be used for makeup air, by means of devices placed in each room (an example in Fig. 10.8). During summer, cooler fresh makeup air can reduce the room thermal energy need for air conditioning, thanks to the decrease of room thermal load. The use of extracted air behind vertical greening systems for natural ventilation (makeup air) represents an interesting option to exploit the cooling capacity of vegetation. In addition, a pressure difference between the

[1]The indoor temperature used for calculating the energy need for space cooling in *Italian standard UNI/TS 11300-1.*

Table 10.4 Monthly average temperatures, calculated during office hours (from 8 AM to 6 PM), of air extracted from the two ducts, with and without influence of the VGS and monthly number of office hours (from 8 A.M. to 6 P.M.) during which the air exceeds 26 *°C*

Month	Air extracted from outside [°C]	Number of hours that air, extracted from outside, temperature exceeds 26 °C	Air extracted behind vertical greening system [°C]	Number of hours that air, extracted from outside, temperature exceeds 26 °C
June 2015	26.5	119	21.3	0
July 2015	29.8	208	24.6	19
August 2015	27.3	143	22.7	6
September 2015	23.0	44	19.2	0
June 2016	25.6	77	22.6	0
July 2016	23.8	161	21.7	0
August 2016	21.3	112	18.3	0
Septembe 2016	23.2	7	21.1	0
June 2017	22.2	138	20.7	0
July 2017	25.6	125	23.7	0
August 2017	26.3	117	20.1	0

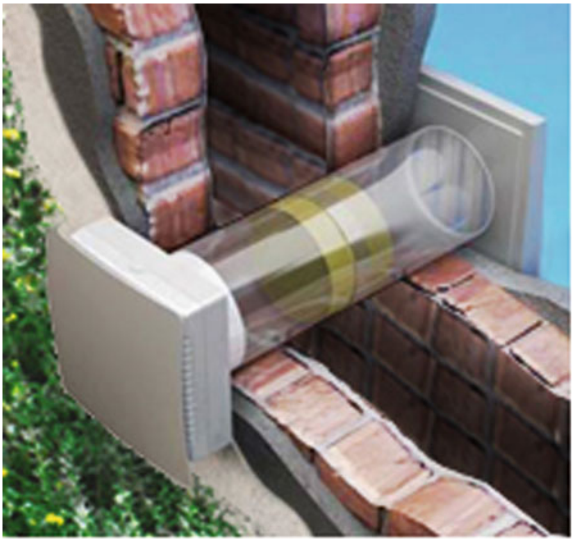

Fig. 10.8 Example of a fresh air inlet device

side of a building with a greening system and the roof and or another façade could be exploited. For mechanical ventilation additional research is needed in order to evaluate the cooling capacity of a vertical greening system with higher air flows.

The presented results show that vertical greening system could play a relevant role for indoor thermal comfort improvement and energy savings, providing cooler air for mechanical and natural ventilation.

10.6.2 Experimental Research Results in Lleida, Catalonia (Spain)

During the last decade, set of experimental investigations focused on the study of green roofs and vertical greening systems have been conducted at the University of Lleida (Catalonia, Spain). Main objective of these experiments was the study of these nature-based solutions contribution to passive energy savings in buildings while sustainable criteria were applied to the new designed solutions.

In all of them, the great potential of these systems to improve the thermal performance of the building envelope was observed, which entails great savings in energy consumption as result of the combined effect of the shadow, evapotranspiration, insulation and wind barrier, mainly provided by plants and substrates.

Unlike the grey infrastructure, urban green infrastructure also contributes via cooling effect to the improvement of the environment, whether internal or external, thanks to the modification of the temperature and relative humidity in its surroundings. Latent heat of water vaporization accounts for 2.45 MJ Kg^{-1} (20 °C), and this takes place both from plants and from substrates during the process of evapotranspiration. By means of the combination of this process and ventilation, either natural or artificial, it is possible to shift these improvements though the building spaces.

Green roofs

<u>Experimental set-up on the thermal performance of extensive green roofs.</u>

In this study it was intended to measure the potential of extensive green roofs as a passive energy saving system in buildings under Mediterranean continental climate. Two identical extensive green roofs of 9 cm thick (4 cm for drainage layer and 5 cm for substrate layer) were implemented in two identical 3 × 3 × 3 m experimental cubicles. The main aim was to characterize their contribution as passive energy saving systems in buildings [51–53]. The only difference between these green roofs was the drainage material used, that was pozzolana in one cubicle and recycled rubber crumbs in the other. These two cubicles, in which no additional insulation layer was installed on the green roof profile, were compared with a third reference cubicle with a conventional flat roof insulated with 3 cm of sprayed polyurethane, finished with gravel ballast (Fig. 10.9). The plants used were a mixture of *Sedum sp.* and *Delosperma sp.*

From the results of this experimentation it was concluded that a 9 cm extensive green roof without additional insulation offered better thermal insulation than a conventional isolated flat roof in cooling periods, but lower in heating periods. The

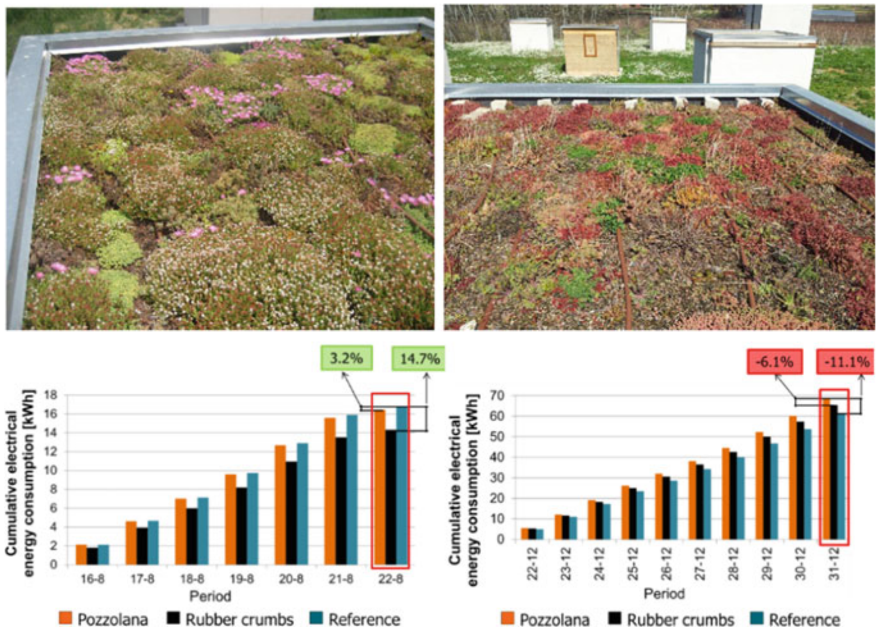

Fig. 10.9 Experimental extensive green roofs in the “Puigverd de Lleida” pilot plant of GREiA research group—University of Lleida. Pictures and results for the energy consumption during summer (left) and winter (right) periods [51–53]

measured reductions on the roof surface temperatures were a clear indicator of the influence of shade and cooling effects on the energy consumption reduction.

10.6.3 A Case Study. 4-Year Monitoring of Green Roofs at Lleida Agri-Food Science and Technology Park (Catalonia, Spain)

With the aim of characterizing the thermal behavior and the evolution of the plants (*Sedum sp.*), an extensive 2000 m^2 green roof located in the Lleida Agri-food Science and Technology Park (Catalonia, Spain) was monitored during four years after its implementation [54, 55] (Fig. 10.10).

From this experiment, very interesting conclusions were drawn regarding the substrate behavior and the fact that 100% plant coverage was hardly achieved under this Continental Mediterranean climate. These facts had a double connotation. On the one hand, the bare substrate becomes extremely hot on surface, reaching more than 50 degrees during the summer season. On the other hand, the lack of rain water available for long periods can reduce the cooling effect at times that are most needed,

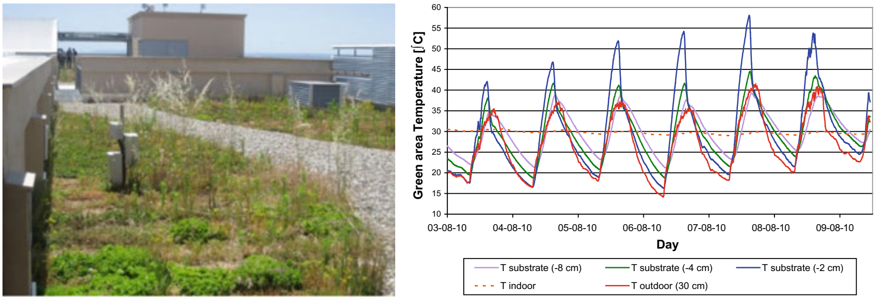

Fig. 10.10 Green roof "aljibe" typology on the Lleida Agri-food Science and Technology Park (Catalonia, Spain). Results for temperatures through the roof profile [54, 55]

that is summer periods. For this reason, it is very important to design systems thinking not only on the plant survival but also about the ecosystem services provided by green infrastructure, in this case the evaporative cooling effect.

In this regard, the establishment of an irrigation regime in extensive green roofs during the summer periods for these extreme climates would allow improving the vegetal coverage and, at the same time, increasing the evapotranspiration capacity and consequently the cooling effect of the system.

Vertical greening systems

Experimental set-up on the thermal performance of vertical greening systems (VGS).

In a complete experimentation, two different vertical greening systems were installed in two identical experimental cubicles of 3 x 3 x 3 m with the objective of evaluating their potential as passive systems of energy saving in buildings [53, 56, 57] (Fig. 10.11). In the first cubicle, a green facade was implemented in the East, South and West orientations, by means of a steel mesh separated 20 cm from the building facade and Boston ivy (*Parthenocissus tricuspidata*). On the second cubicle, a green wall, constituted by modules of recycled plastic and aromatic shrubs (*Rosmarinus* and *Helicrissum*) was also placed on the same three orientations. A third identical cubicle in which no one greening system was placed was used as reference for the experimentation.

In this experiment, positive results were obtained so that the ability to save energy during summer periods was really very high. The relationship between the vertical solar irradiation and the reduction of the energy consumption provided by the two vertical systems was also found (Fig. 10.11).

In winter, unlike what is usually said in the non-specialized bibliography, very promising results were observed. Thus, relating to green facade, the cubicle on which this system was placed, behaved equal to the reference cubicle as it was expected, due to the deciduous condition of Boston ivy. On the other hand, the green wall cubicle recorded a slight reduction of 4%, which means a slightly insulating capacity but with a large margin for improvement in the design of these construction system.

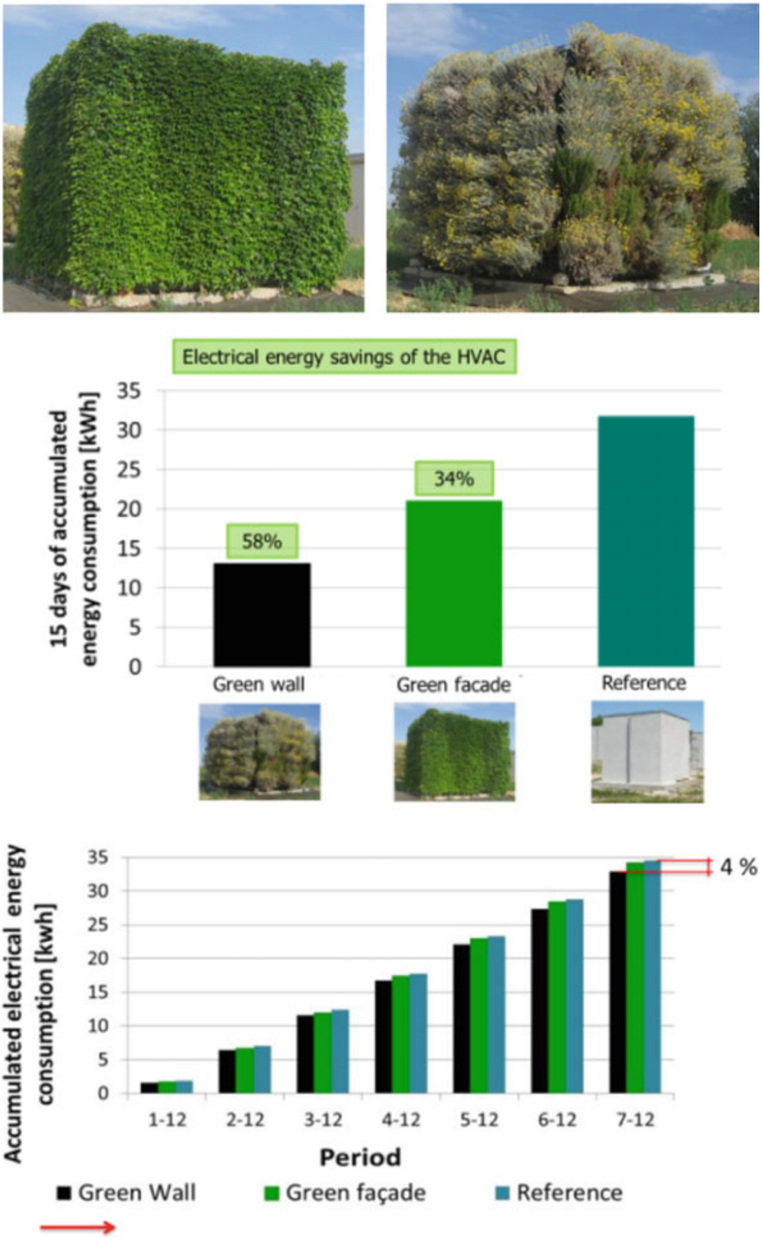

Fig. 10.11 Left: Green facade on the experimental cubicle and results of summer energy consumption. Right: Green wall on experimental cubicle and winter results [53, 56, 57]

Although in these experimentation the passive use of VGS for energy savings was the main aim, the good performance of green systems by reducing the surface temperatures of façade building, due to the shadow effect, and the contribution of evapotranspirative cooling from plants and substrates, suggest an interesting potential to combine them to the mechanical ventilation systems.

10.6.4 Case Study. 2-Year Monitoring of a Double-Skin Green Façade at the Theatre of Golmés Green Facade (Golmés, Catalonia, Spain)

In this study, a glycine double-skin green façade (*Wisteria sinensis*) located in the village of Golmés, Lleida was monitored during two years. From this case study, interesting conclusions regarding the potential of green facades as passive systems of energy saving in buildings were obtained [58, 59] (Fig. 10.12).

Fig. 10.12 Golmés double-skin green facade (Golmés, Catalonia, Spain)

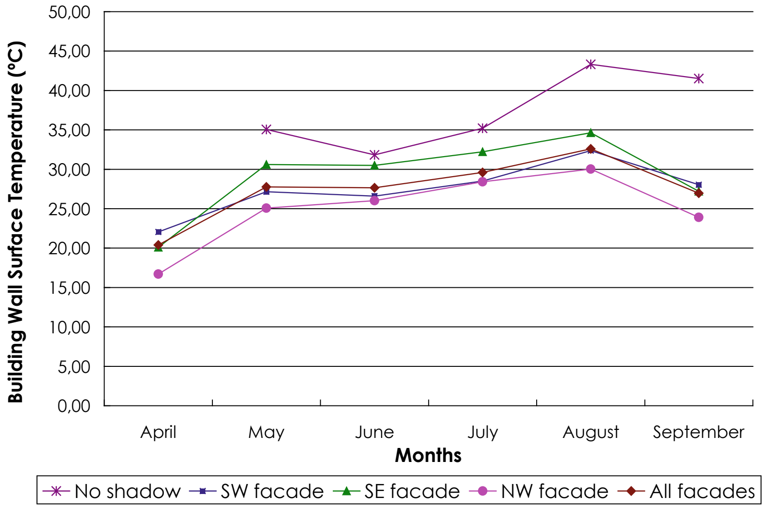

Fig. 10.13 Building wall surface temperature measured at the Golmés green façade, in 2009

The good thermal performance was due to, not only the shadow effect, that is the direct interception of the solar radiation, but specially as a consequence of the microclimate generated in the intermediate space between the green screen and the building facade wall. In this sense, the contribution of the cooling effect by means of transpiration from plants was very significant.

As a consequence of greenery the building wall surface temperature in sunny areas was on average 5.5 °C higher than in shaded areas. This difference was higher in August and September, reaching maximum values of 17.6 °C on the North West side in September (Fig. 10.13).

Of particular interest were the measured temperatures and relative humidity in the intermediate space between the green screen and the building façade wall. Slightly lower temperatures and higher relative humidity in the intermediate space than outside were measured in the hottest months (May, June, July, and August), when the foliage reached the maximum foliage density (Fig. 10.14).

Again, in these experiments only the passive contribution of the VGS was measured. However, the good results obtained, especially those referring to the improvement of humidity and temperature conditions in the intermediate space between the green screens and the building facade, imply a great potential to be combined with ventilative cooling systems to consequently improve the thermal performance of the whole building.

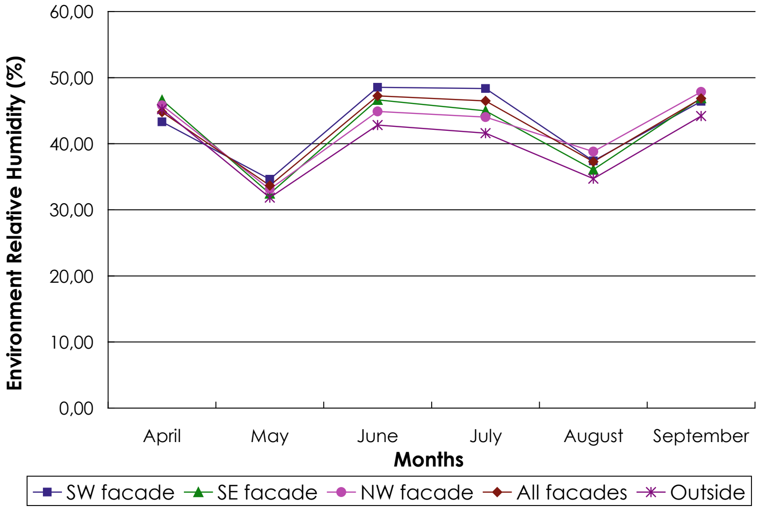

Fig. 10.14 Environment relative humidity measured at the Golmés green façade, in 2009

10.7 Suggestions for Future Research

At view of the great potential in terms of passive cooling effect of greening systems for the building envelope, in particular of vertical greening systems, research should be oriented at the activation of these systems. Such activation can be obtained by recirculating the fresh air generated in the spaces near the green layer toward indoor spaces of the building. In order to implement such systems, the current construction systems should be re-designed with the aim of maximizing the cooling potential, for example by considering the creation of intermediate spaces between vegetation and buildings to store fresh air.

Other possibilities would be to select plant species for greening systems with a greater water transpiration capacity, as well as to establish different irrigation regimes to maximize evapotranspiration. Finally, future research should be oriented to the integration of cool air produced by greening system into building ventilation facilities.

In general, urban greening, even if not connected with the ventilate system of a building, can play an important role in cooling the microclimate, compensating the effect of electrical appliances and machinery, as well as indoor-outdoor heat exchanges that produce artificial air conditioning systems.

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Part III
Applications

Chapter 11
Ventilative Cooling in Residential Buildings

Paul D. O'Sullivan

Abstract This chapter describes how to integrate and use ventilative cooling (VC) in residential buildings. A large set of case studies is introduced and classified in order to better define solutions for different climate and residential building typologies. Furthermore, the potential effect of ventilative cooling is analysed while design choices and techniques used are outlined.

Keyword Residential · Cooling ventilation · Comfort

11.1 Summary

The following summary section covers a brief introduction to Residential VC, chapter highlights, key findings for Residential VC and Limitations to the application of VC in residential buildings.

Brief introduction

Up to now, for residential buildings, the design process is much more simplified than for commercial buildings and, to a very large extent, based on experiences and rules of thumb with the result that many solutions exist but their performance in-use is hampered by overly-simplified design stage performance checks and improper operation by occupants. With the ever-tightening grip national building regulations increasingly have on the heating energy performance of residential buildings, particularly in more northern climes, Ventilative Cooling (VC), is now an important consideration for residential designers to minimize the energy consumption of homes. The following chapter highlights various different VC principles, strategies and components that have been adopted to address the increasing challenges associated with the interdependent relationship between dwellings and their surrounding environment. The features of case studies presented will be used in the chapter to demonstrate different best practice approaches to residential VC.

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Highlights

The scope of this chapter can be summarised with the following chapter highlights:

- 9 different residential ventilative cooling strategies that combine principles, systems and components are presented
- 16 exemplary residential case studies of ventilative cooling that apply the 9 different strategies in various ways are mapped and summarised
- Real in-use building examples of ventilative cooling principles, strategies and components are used to assist in demonstrating their application and their performance
- Measured performance of 4 well documented residential case studies of ventilating cooling are presented

Key findings for residential VC

Some key findings for residential VC are:

- Simple VC solutions that maximize the site-dwelling interactions and dwelling morphology have been shown to perform best.
- In homes the users are non-technical and non-expert suggesting that the VC solutions should be simple enough to be fully understandable and operable ensuring they are not misused with the associated underperformance
- Mechanical ventilation is very common in residential properties nowadays and this can be used to enhance VC potential.
- The resilience to future overheating even in exemplar properties is still a major challenge and has not been fully explored outside of research communities, with design practices not properly addressing future proofing, particularly in climates where the dominant design culture is to reduce heating consumption.
- VC works in residential applications but more documented case studies are needed, particularly those associated with social housing, elderly housing and high density urban residential zones that provide valuable datasets and lessons from design and building practice that can inform policy and regulations.

Limitations of residential VC

Typically, given the cooling load profile and building morphology of residential homes, the potential for using VC is not significantly limited beyond the following considerations:

- The developed solutions to address cooling issues available for residential applications are somewhat limited and often too simplified and might not be well adapted for practical application.
- In the few cases, where the cooling challenge is addressed by a "one-of-a-kind" design, the solutions can be expensive and need careful commissioning to function.
- The end users are non-expert and systems very often do not operate in practice as intended in design resulting in underperformance.

- The climatic suitability of residential VC means it is generally not appropriate for providing air to homes other than for minimum hygienic ventilation purposes during daytime hours in hot and dry climates and during both daytime and nighttime in hot and humid climates.

11.2 Introduction

Up to now, for residential buildings, the design process is much more simplified than for commercial buildings and is to a very large extent based on experiences and rules of thumb. To reach a low energy need for heating, designers typically apply guidelines for passive solar buildings developed in the past, where insulation and airtightness levels were far from the levels of today, and as a result they underestimate the need for cooling or might not even take it into account. For this reason, and with the ever tightening grip national building regulations have on the heating energy performance of residential buildings, particularly in more northern climes, VC is now an important consideration for designers.

Prediction of energy use in residential buildings is often based on simplified monthly methods and it is estimated for the residence as a whole. Averaging the need for cooling in both time and space underestimates the total cooling demand [1]. Excess heat in spaces exposed to solar radiation is considered to be distributed fully to other spaces and excess solar radiation during daytime is partly distributed to night-time. Due to these simplifications, the real need for cooling to ensure acceptable temperature levels in all spaces will be higher than the predicted one. The analysis of the risk of overheating is typically based on the calculated cooling need and typical compliance tools used do not facilitate a calculation of the cooling effects together with the thermal evaluation of the building. Unfortunately, there is no correlation between the calculated cooling need with these simplified methods and the actual number of hours with elevated temperatures [1]. So, even if no cooling need is predicted and designers do not expect overheating problems, the number of hours with elevated temperature levels can be considerable.

Cooling and overheating in residences have so far not been considered a design challenge, especially in colder climates. Therefore, the developed solutions to address cooling issues available for residential applications are very limited, often too simplified and might not be well adapted for practical application. In the few cases where the cooling challenge is addressed by a "one-of-a-kind" design, the solutions can be expensive and need careful commissioning to function.

In recent years there has been an increase in the use of mechanical solutions to ventilation supply in residential buildings in the form of heat recovery devices, largely to reduce heating loads resulting from ventilating indoor spaces directly using cold outdoor air through wall vents and windows. However, these mechanical systems can be employed for delivering outdoor air at times when there exists a sufficient cooling potential to offset heat gains during cooling periods. Further, strategically positioning openable windows throughout the residential property can also enhance the ability of the buildings architectural features to help offset heat build up as a result of the inability of the high performance envelopes to dissipate heat following the thermal decoupling from the airtight low conduction characteristics.

The following chapter highlights various different VC principles, strategies and components that have been adopted to address the increasing challenges associated with the interdependent relationship between dwellings and their surrounding environment. Table 11.1 presents a number of completed residential buildings that have incorporated VC characteristics into their design [2–4]. The features of these case studies will be used in the chapter to demonstrate different best practice approaches to residential VC.

VC principles in residential buildings can vary, primarily depending on geographical location and climate. Understandably, in hotter climes VC may form part of an overall strategy which also includes mechanical cooling.

Table 11.2 summarises appropriate VC approaches that should be adopted based on outdoor climate. Often VC in residential applications will involve simplified solutions such as wind driven air flow through openable windows, buoyancy driven air flow through roof windows and mechanical ventilation. In some special cases there are examples of more advanced strategies such as earth to air heat exchangers and night cooling. In order to better classify the various types and approaches to VC the following sections deal separately with principles (i.e. driving forces exploited), strategies (i.e. whether night cooling or mechanical ventilation might be adopted) and components (i.e. windows, vents, doors etc.) before presenting some well documented examples of these and their associated measured performance.

11.3 Residential Ventilative Cooling Principles

Residential applications of VC generally require low complexity, simple to use solutions for occupants. In many instances this can be achieved through careful design exploitation of the local microclimate, the site surroundings and their interaction with the building morphology. The complimentary relationship that climate and building can use to improve the climatic cooling potential of a dwelling begins initially with the architectural design, attempting to configure the indoor spaces and enclosing envelope in such a way that it maximizes the utilization of the energy potential in the outdoor air at times when the potential for cooling is adequate to maintain a satisfactory indoor thermal environment. In addition to positioning the house strategically within its surroundings the house morphology itself can be defined in such a way as to reduce the incidence of cooling loads in the interior while enhancing airflow through the space to remove any build-up of unwanted heat. To achieve this architectural blueprint for VC exploitation a number of different architectural principles and strategies can be adopted. Examples of these different principles available in the literature can be categorized according to whether they exploit the site-dwelling interaction, the dwelling morphology or wind and thermal forces acting on the air mass across the ventilation openings. These are addressed separately below.

Table 11.1 List of residential buildings adopting ventilative cooling referenced throughout chapter (See Table 11.3 for description of strategies)

References	Name, Location, Country	Completion Year, Climate	Key Features	VC Principles	VC Strategy
01	**Zu-haus** Auersthal, AT 	2013, Cfb	Foliage south of the building for shading purposes; Optimized orientation north-south; Form and window positions optimized for natural ventilation; Overhanging roof in the south provides shading	CV, Stack	NV-NC
02	**Sunlight House** Pressbaum, AT 	2010, Cfb	Increased room height for air flow paths; additional thermal mass in basement using exposed concrete; Windows positioned strategically to make use of the stack effect; total window surface area represents 42% of useable living area	CV, Stack, SSV	NV-NC, MVHR

(continued)

Table 11.1 (continued)

References	Name, Location, Country	Completion Year, Climate	Key Features	VC Principles	VC Strategy
03	**Student House** Vienna, AT 	2005, Cfb	Large trees act as shading devices in front of building; Passive house design; light wells function as chimney in stair cases; external shading	CV, Stack, SSV	NV-NC
04	**Wohnen Mühlgrund** Vienna, AT 	2011, Cfb	Evaporative effects from external garden along entire north façade; Ventilated corrugated metal façade protects against noise pollution; heavyweight thermal mass construction	Stack, Mixing, CV	NV-NC, MVHR, EVAP-C
05	**Venus Garden House** Willendorf, AT 	2013, Cfb	Building aligned parallel to a riverbank along prevailing wind direction; Internal spatial arrangement enhances the internal airflow from ground to attic rooftop windows via staircase; Openable windows to the north avoid overheating	Stack, Mixing, CV	NV-NC, MVHR

(continued)

Table 11.1 (continued)

References	Name, Location, Country	Completion Year, Climate	Key Features	VC Principles	VC Strategy
06	**Home for Life** Lystrup, DK 	2009, Cfb	Window openings and skylights placed strategically to enhance natural ventilation; Doubled pitched roof with off centre ridge to accommodate large south facing roof surface for maximum energy generation.	Stack	NV-NC
07	**Passivehouse Pichler** Pfitsch, IT 	2009, Cfb	Tree planting in front of south western and northern sides of building.	Stack	NV-NC, MVHR
08	**MOMA Apartments** Changsha, CN 	2007, Cfa	Sealed windows, floor level air supply, window to wall ratio is 18%	Free Cooling, Mixing	MVHR, AC-FrC
09	**Maison Air et Lumiere** Verrieres-Buission, FR 	2014, Cfb	Active house principles, 31% window wall ratio, careful positioning of façade and roof windows, high performance envelope	Stack Effect	NV-NC, MVHR

(continued)

Table 11.1 (continued)

References	Name, Location, Country	Completion Year, Climate	Key Features	VC Principles	VC Strategy
10	**Mascalucia ZEB** Sicily, IT 	2013, Csa	PassivHaus Certified, layout and patio design studied to enhance NV, window wall ratio 25%, U shape design with higher POF, very heavy thermal mass	CV	NV-NC, EAHE, MVHR, DCV
11	**Living Lab** Trondheim, NO 	2014, Dfc	ZEB, solar energy exploitation, very high envelope thermal performance, window to wall ratio 17%, light thermal mass,	SS, CV, Stack	NV, MVHR
12	**Energy Flex House** Taastrup, DK 	2009, Cfb	Limited glazed areas on South façade, solar shading (external and internal), exposed thermal mass	CV, Stack	DCV (NVHR), DCNV-NC, M-NC
13	**Eco Home** Shanghai, CN 	2010, Cfa	Building orientation designed around prevailing monsoon direction, balcony design to promote shading effects	CV, Stack	NV-NC, EVAP-C, M-E

(continued)

Table 11.1 (continued)

References	Name, Location, Country	Completion Year, Climate	Key Features	VC Principles	VC Strategy
14	**Cascicline in Bernate** Milan, IT 	2013, Cfa	Uses a radiant wall system, natural wooden surfaces plastered with natural clay including heating panels in clay. Large external overhangs for ground floor, external first floor lamellas. Window design to increase cross ventilation, high airtightness, high thermal mass	CV, Ground Cooling	NV-NC
15	**Lixil Passive Pavillion** Toyota, Aichi, JP 	2014, Cfa	Large windows on the windward wall (summer), limited partition walls, glass louver windows on the roof for exhaust through living room and stairwell, airflow guiding balcony walls, deep eaves and balcony provide shading	CV, Stack	NV-WD

(continued)

Table 11.1 (continued)

References	Name, Location, Country	Completion Year, Climate	Key Features	VC Principles	VC Strategy
16	**M-Smart City** Kimagaya, Saitama, JP 	2014, Cfa	Low-e coated double glazed windows. Evaporative cooling techniques throughout	CV, Mixing, Stack	NV-NC, AC, MM, EVAP-C

Table 11.2 Overview of typical Ventilative cooling strategies applied depending on outdoor climatic conditions and type of ventilation system [1]

Temperature Difference	Ventilative Cooling	Supplementary Cooling Options
Cold ($\Delta T > 10$ °C)	Minimize air flow rate – draught free air supply	Not applicable
Temperate (2–10 °C below comfort zone)	Increasing air flow rate from minimum to maximum	Strategies for enhancement of natural driving forces to increase air flow rates Natural cooling strategies like evaporative cooling, earth to air heat exchange to reduce air intake temperature during daytime
Hot and dry (-2 °C $< \Delta T <$ 2 °C)	Minimum air flow rate during day time. Maximum air flow rate during night time	Natural cooling strategies like evaporative cooling, earth to air heat exchange, thermal mass and PCM storage to reduce air intake temperature during daytime Mechanical cooling strategies like ground source heat pump, mechanical cooling
Hot and humid	Natural or mechanical ventilation should provide minimum outdoor air supply	Mechanical cooling/dehumidification

11.3.1 Site—Dwellings Interactions

There are a number of different characteristics that can be exploited to enable the utilization of VC for effective cooling.

- **Prevailing Winds**: Orienting the main occupiable spaces with respect to the prevailing cooling season wind direction to maximize airflow into the interior.
- **Solar Radiation**: Limiting glazing apertures on south façade and combining with external overhangs to prevent high angle summer solar radiation. Internal shading can be considered but this does not prevent the incidence of solar loads into the space. Examples include: balconies, roof overhangs and first floor staggered designs.
- **Internal Obstructions**: Limiting partition walls to reduce internal airflow obstruction allowing good air movement across the dwellings where possible. Examples include: open plan living and dining, direct access to rooms from open plan spaces, moveable partitions.
- **Evaporative effects from site**: designing with the use of local rivers or lakes/ponds to reduce the temperature of incoming outdoor air. Use of external vertical gardens to promote additional evaporative cooling.
- **Local Flora**: tree planting certain species to promote natural shading while using densely packed species to act as a bluff body redirecting site scale airflow into the dwellings.

The features identified above can be found in case studies 03, 04, 07 and 13 from Table 11.1.

11.3.2 Dwelling Morphology

- **High level roof openings**: Skylights and roof windows positioned within stairwells and top floor stairs landing areas can substantially enhance the amount of airflow through lower level habitable spaces. These openings can be automated or manual and should be designed in conjunction with the lower level openings to ensure the correct flow regime to provide cooling is properly established with the neutral pressure level correctly located.
- **Heavy thermal mass**: While exposing thermally heavyweight materials, (such as cast concrete for example), that can act as indoor air temperature stabilizers and heat sinks is a significant and generally uncommon aesthetic decision in a dwelling, there can be measurable benefits to future proofing the indoor habitable spaces to overheating. Utilizing materials with a high heat capacity can reduce the temperatures of the indoor space by absorbing solar gains and delaying their re-entry to the indoor air mass to a time later than daily peak outdoor air temperatures. Strategically positioning air flow intake locations to coincide with exposed thermal mass can lower the incoming air temperature thus enhancing the cooling potential

of the VC strategy. Examples include: exposed concrete in basements and garages where the intake airflow path for the habitable spaces is directed; earth ducts for intake air; painted concrete finishes within habitable spaces.
- **Light-wells/chimneys**: Light-wells and chimneys can be effective at increasing buoyancy driven airflow rates by extending the overall height between inlet and outlet for airflow strategies. These can also provide a good opportunity to further enhance airflow by exploiting the effects of solar gains on increasing the temperature differences between inlet-outlet locations. However, there are architectural considerations that need to be considered for these solutions and local planning regulations may restrict their incorporation to dwelling design.
- **Window design**: The selection of window opening characteristics (sash, top hung, bottom hung, inward opening, outward opening etc.), the design of the shape including its area as well as its aspect ratio can all contribute to enhanced airflow rates and increased air velocities within the space which improve cooling performance.
- **High thermal performance**: Limiting the incidence of heat gains in the first instance is an effective strategy reducing the demand on the VC system to maintain comfort conditions. This can be done by effective orientation of the dwelling, exploiting local shading from surroundings and dwelling features, increase in exposed thermal mass amongst others.

The features identified above can be found in case studies 02, 03, 04, 06, 09, 10, 11, 12 and 14 from Table 11.1.

Having incorporated where possible the principles above these should contribute to the following key design objectives for climates that have suitable conditions for VC:

- Lowering incoming air temperatures
- Enhancing the air velocities and airflow rates
- Reducing incident solar gain

The next phase in the design evolution for dwellings with good VC cooling capabilities is to consider the ventilation and airflow principles. There are a number of approaches that can be taken to introduce air from an outdoor source into the indoor space, allow that air to then absorb heat and to carry that heat out of the interior and discharge it in a heat sink. Avoiding contamination of inflow/outflow paths can further reduce short circuiting and improve performance. Best practice case studies generally utilize one of two principles for providing ventilation: wind driven, (WD), and/or buoyancy driven cross ventilation and/or buoyancy driven stack ventilation. To a lesser extent single sided ventilation, (SSV), and mixing ventilation are also adopted.

11.3.3 Wind Driven Cross Ventilation

Cross Ventilation, (CV), occurs where there are ventilation openings on both sides of an indoor space in the dwelling. This is generally achieved by inflow through open windows and outflow through doors leading to corridors that lead to the outside or alternatively through directly connecting directly to the outside [5]. CV flows are characterized by significant inflow momentum conservation as fluid flows across the enclosed indoor space as a confined jet [6]. This type of flow can result in two distinct flow regions in the indoor space. Depending on the wind direction and configuration of openings in the dwelling the relationship between these regions will be different. CV has been shown to generate large airflow rates, for example in some instances air changes rates, (ACR), of greater than 20 are possible resulting in efficient heat removal rates even at low temperature differences [7]. However, at these high ACR there can be issues around thermal comfort and practical disturbances. In general CV can be very effective and easily incorporated where there are direct airflow paths through the habitable spaces from inflows through porch doors or windows and outflow through central stairwells, light-wells, adjacent façade windows etc. Careful consideration should be given to allowing depleted stale warm air from one zone to pass through another zone as part of its outflow path thereby negatively contributing to the thermal environment in that zone. Of the 16 case studies in Table 11.1 twelve of them identified CV as a VC principle.

11.3.4 Buoyancy Driven Stack Ventilation

Stack driven ventilation, (SD), is driven by density differences across the indoor space with cooler dense air drawn in at low level and warmer less dense air exhausted through a defined vertical outflow path. In effect, where there are physically separated inflow and outflow locations this is a sub category of CV. A general rule of thumb for this type of ventilation principle is its suitability to ventilate spaces with a depth up to about five times the floor to ceiling height, making it appropriate for many dwelling configurations. Of the 16 case studies in Table 11.1 thirteen of them identified Stack Ventilation as a VC principle suggesting it is a principle easily integrated into residential building design.

11.4 Residential Ventilative Cooling Strategies

A range of different strategies can be employed for a given VC principle depending on how the components and airflow are controlled. VC strategies may also be integrated with other strategies depending on whether there is a mixed mode approach in place or whether there is enhanced cooling strategies employed. Generally, when

Table 11.3 Summary of different VC Strategies employed in exemplar dwellings (these adopt one or a number of principles for VC)

Strategy	Name	Comment
NV	Natural Ventilation	Large implementation rates in residential VC with WD-CV and SD-CV used in almost all dwellings
NC	Night Cooling	Requires some additional features; has barriers to implementation
MVHR	Mechanical Ventilation With Heat Recovery	Used for Heating season to reduce heating demand loads; can be used for VC but risk of thermal cross contamination.
DCV	Demand Controlled Ventilation	Employed in residential dwellings where automated solutions in place. Often in combination with MVHR
MC	Mechanical Cooling	Only present in special cases with VC supplied through free cooling when available
FrC	Free Cooling	Normally as part of a mechanical ventilation/cooling strategy where bypass dampers allow direct supply of air to the indoor space
EVAP-C	Evaporative Cooling	Provided usually in combination with NV, lowering inflow temperatures using evaporation of moisture from vegetation and rivers/lakes
EAHE	Earth to Air Heat Exchanger	Special cases; lowering inflow air temperatures enhancing cooling potential
GC	Ground Cooling	Special cases only;

employing VC in residential applications simple easy to control strategies can be the most appropriate for homeowners. The most common approaches in exemplar residential case studies are different combinations of the technologies and processes in Table 11.3. Table 11.1 identifies which strategy is employed in each case study dwellings. A description of some key examples of how these VC strategies are used in residential dwellings are summarised below.

11.4.1 Case Study 05—Venus Garden House, Willendorf, AT. (VC Strategies: NV-NC, MVHR)

The ventilation approach at Willendorf Venus Garden House in Austria is adjusted according to the season. During the heating season when the ventilation requirements are driven by indoor air quality, the controlled decentralized MVHR system ventilates the building. During the other times of the year automated windows, which can be manually over-ruled, are utilised. The windows are activated and mechanised using chain actuators. Sensors measure the CO_2 concentration of the room air and operate the windows accordingly. During summer, the ventilation system is equipped with bypass dampers to prevent unintended overheating of the rotary regenerative heat exchanger.

11.4.2 Case Study 13—Eco Home, Shanghai. (VC Strategies: NV-NC, EVAP-C, M-E)

At the Shanghai Eco Home case study Night Cooling is employed when the outdoor temperature is below 28 °C and velocity is below 7 m/s. This normally occurs during the dry summer nights (normally between 20:00 and 07:00). In spring and autumn supplementary lowering of inflow air temperatures is achieved by filtering the air through vegetation in the vertical garden and across the landscaping pond outside the south semi-basement prior to entering the indoor spaces. In spring and autumn the airflow is cooled by running through the vertical plants and landscape pond outside the south semi-basement before entering into the building through the opened windows. Multiple horizontal airflow corridors were directed through the "Ecological nuclear" atrium and buoyancy driven stack ventilation was utilized as a principle for outflow of stale warm air through high level windows at the top of the atrium. Windows were designed on the side of the top of the atrium as the outlet, combining the mechanical fans to increase the efficiency of natural ventilation. In addition, the elevators with potential energy recovery and variable speed function activated the movement of the airflow as they moving up-and-down.

11.4.3 Case Study 14—Casaclima in Bernate, Milan, IT. (VC Strategies: NV-NC, M-C, G-C)

A number of morphological strategies are employed at Casaclima to support the VC approach. The south-west façade of Casaclima presents a ventilated cavity in order to enhance the wall transpiration improving the thermal behaviour during the cooling season. A covered balcony at the upper floor smooths the external temperature variations when windows are kept open during the mid-seasons. The floor overhangs limits the shading period to the hot hours when the sun is at the zenith. The shading at the first floor is guaranteed by an external lamellae system, activated by external light sensors. Several windows installed at the southern façade for the exploitation of solar gains in the winter time and windows on all sides to enable cross-ventilation in the summer time. A green roof at the upper floor helps to cool down the building by evaporative transpiration. Foundations are also ventilated to remove heat build-up thus offering additional heat storage. Regarding ventilation and cooling technological solutions no mechanical ventilation systems are used, since the cooling strategy is based on thermally coupling the natural ventilation airflow with the heavyweight thermal mass delivering a time lag of more than 12 h between peak incident solar radiation and peak indoor temperatures, largely due to the walls. A dehumidification system has been considered necessary in order to cope with the high humidity levels in summertime. CV is exploited when possible. A fan coil dehumidification system is used during the cooling season and a radiant wall system is supplied by ground cooling using a geothermal heat pump to provide the remaining peak cooling loads.

Selection of individual VC components are the remaining part of defining a suitable VC approach for a residential building. Broadly speaking these are simple components that do not require sophisticated controls or expert knowledge to ensure their correct functioning. Advanced components requiring a high level of expertise to efficiently operate should be avoided in residential applications given the non-expert users. Otherwise the poor operation can negate any of the potential benefits from exploiting a VC strategy over full mechanical cooling.

11.5 Residential Ventilative Cooling Components

Depending on the combinations of principles and strategies adopted a range of components can be employed when using VC in residential applications. While not always, in residential applications these components are often architectural in nature being integrated into the building fabric, rather than mechanical components supplementary to the architectural form. In this way VC in residential buildings can be provided with a low aesthetic impact and in harmony with the underlying architectural daylighting and solar design. Where a mechanical system is used for providing VC this is often concealed or integrated as much as possible. Examples of appropriate components for residential VC are summarized below. Typical strategies are identified for each.

- **Façade Windows**. These are the most common components in residential applications for providing fresh air for cooling. Openable windows can be set to a certain opening percentage to regulate the airflow into the dwelling. Depending on the window design performance varies and certain window types are more suitable to different principles of VC. An exhaustive discussion on this is available in the literature [5, 8–10]. Whether CV or SS is adopted will have a large impact on how different window installation configurations will perform. More detailed guidance on window selection is available in [5, 11]. Within the case studies presented in this chapter roof-lights are a dominant type employed.
- **Roof Windows**. In many exemplar residential VC applications buoyancy or stack ventilation through the circulation areas (stairs and landing) is used to remove build-up of heat gains in the living areas. This is achieved through the use of high level automated windows, rooflights or skylights that allow warm air exit the dwelling from the living spaces, driven by differences in density with cooler

incoming air through low level faced windows. Roof windows are often automated and operate using a simple control input that is generally either the air temperature in the living zone, the CO_2 concentration levels, or an operative temperature that captures both the effects of air and surface temperatures on an occupants' thermal comfort.

- **Sliding doors**. In residential applications sliding or openable doors directly to exterior spaces are often utilized to dramatically enhance airflow rates and air velocities in indoor spaces. These are useful when the exterior space has some shading such as surrounding flora or awnings, lean-to roofs or balconies overhead, thus providing a slight drop in air temperature of the incoming air.
- **Mechanical Fans**. In many low energy dwellings a mechanical ventilation system is present to provide good indoor air quality and minimum fresh air rates during the heating season. This system can also be utilized (ensuring effective heat recovery bypass functionality) to provide cooling air supply to the dwelling in summer when the driving forces for passive VC are low. However, care must be taken to ensure that the mechanical fans assist exiting airflow regimes such as stack ventilation rather than counter act them reducing the overall VC potential. Fan airflow rates are often controlled using various inputs from indoor air temperature to CO_2 concentration levels.
- **External shading**. External shading is not a component directly providing VC. However, effective shading is an integral aspect of any residential VC strategy. Shading can be used to have two complimentary effects, depending on its design and characteristics; reduce incoming air temperatures and minimize solar gains and subsequent cooling loads. Shading is achieved in residential case studies using external vegetation and flora, tree planting, balconies, awnings and retractable lean-to roofing amongst other solutions. These simple but effective components can substantially extend the range of time when VC is suitable for cooling.
- **Chimneys**. Exhaust air Chimneys can be provided in residential dwellings or apartments using purpose provided chimney components or alternatively through the appropriation of stairwells and other central circulation areas as airflow ducts. Chimneys can enhance the overall height producing flow and can also be designed to enhance the pressure regime at the outlet.
- **Purpose provided louvres & grilles**. Less common as a VC component in residential buildings are louvred systems. These can act as airflow guiding components and also provide an architectural feature when materials such as timber are used. Louvres can offer some solar shading, prevent rain ingress and prevent burglars, thus allowing for a night cooling strategy, while also acting as flow straighteners for air supplies as well as breaking the mixing layer in SSV application. These are not common in residential applications however.

Different combinations of the VC principles, strategies and components discussed above result in a wide variety of approach to low energy cooling in residences. However, given the variable and somewhat unpredictable nature of VC in domestic environments, evidence of good in-use performance is useful when deciding whether or not to pursue a VC solution to the comfort needs of occupants.

11.6 Performance in-Use of Residential VC

A recent International Energy Agency (IEA) [12] project that investigated the potential for VC to minimize cooling loads and reduce the risk of overheating in residential buildings identified 4 well documented residential case studies that had detailed performance evaluations of their VC solutions completed using both simulations and measurement studies. Details relating to the four of these case studies are contained in Table 11.4.

A number of different factors can influence the design of VC in residential buildings. Table 11.5 highlights the key factors that influenced the selection of the VC approach for the 4 case studies in Table 11.3. In reviewing Table 11.5 we see that reducing solar loads and lowering energy costs appear to have a high influence on the design, while reducing external noise, insect prevention and reducing privacy having a low influence on design. Internal loads, internal noise propagation and burglary prevention don't seem to feature highly as influences either. Air leakage was also identified as an important consideration in determining the most appropriate strategy likely resulting in an increase in use of MVHR and NV combined strategies.

The following section presents information from 3 of the well documented case studies to highlight performance of VC in residential buildings. Each section covers the VC strategy, the design approach, and whether any simulations studies were

Table 11.4 Summary details of well documented residential VC case studies [2]

Property	Italy	China	Norway	France
Case Study Number (ref Table 16.1)	10	08	11	09
Surroundings (Urban/Rural)	Rural	Urban	Urban	Suburban
Overarching VC Strategy	NV	MC	NV	NV
Year of Completion	2013	2007	2014	2011
Floor Area (m^2)	144	1109	100	173
Openable Area to Floor Area ratio	14.7%	0%	35%	2.76%
Sensible Internal Load (W/m^2)	2	57	Variable	3.45
Days with max external temp >25 °C	106	84	0	27
Window U Value (W/m^2K)	0.9-1.10	2.0	0.97	1.4
Window G Value	0.1	0.557	0.35-0.69	0.3-0.48
Wall U Value (W/m^2K)	0.13	0.54	0.11	0.14
Roof U Value (W/m^2K)	0.13	0.30	0.10	0.10
Floor U Value (W/m^2K)	0.23	1.58	0.10	0.12
Thermal Mass (ISO 13790)	Very Heavy	Very Heavy	Light	Light

Table 11.5 Factors Influencing selection of VC strategy [2]

Factor	IT	CN	NO	FR
Lower Initial costs	H	H	L	M
Lower maintenance costs	M	M	L	M
Lower energy costs	H	H	H	L
Reducing solar loads	H	H	H	H
Reducing Internal loads	L	L	M	M
Reducing external noise	L	L	L	L
High Internal noise propagation	L	L	M	L
Elevated air pollution	L	L	L	H
Avoiding rain Ingress	L	M	H	L
Insect prevention	L	L	L	L
Burglary prevention	M	M	L	M
Reduced privacy	L	L	L	L
Air leakage	M	H	H	M

completed and finally some key measured performance data. The information below can be found in more detail in the summary reports from IEA-EBC Annex 62 [2].

11.6.1 Case Study 10—Mascalucia ZEB, Sicily, IT (VC Strategies: NV-NC, EAHE, MVHR, DCV) [13]

The Zero Energy Building, located in the municipality of Mascalucia (Catania) in the region of Sicily, is certified according to the PassivHaus standard. The building exploits VC principles and strategies such as CV and NV-NC. The external patio and the layout of the window openings have been studied to enhance airflow rates. The remaining energy need is covered by (i) the local production of renewable energy by means of photovoltaic modules, (ii) a thermal solar system coupled to a heat pump and (iii) an EAHE coupled to the MVHR system. In particular, the EAHE provides pre-heating or pre-cooling to the fresh air entering the MVHR system. The building is automatically controlled by a building automation system supported by KNX protocol.

VC strategy

The building has been designed to exploit CV in the kitchen-living room, in the study room and in two bedrooms. In addition, the large openings in the living room promote high airflow rates, the entrance of daylight and a view on the garden. During mid seasons and in summer time, the building allows the occupants to adopt NV-NC (provided that the external air temperature is 2 °C lower than the internal air temperature). The dwelling employs external automatic shading in the form of blinds to reduce incoming solar heat gains. The central patio allows better exploitation of cross flow ventilation. The EAHE is used for pre cooling of outdoor air supply to the mechanical ventilation system.

Design approach

The fans' speed is adjusted according to the measured level of carbon dioxide (CO2), Volatile Organic Compounds (VOC) and Relative Humidity (RH). The MVHR is disabled when one of the windows or the entrance door is left open for a certain time (1 min or higher, depending on the setting). Depending on the condition of the indoor air temperature the fan speed is adjusted to provide an airflow rate for cooling needs or for IAQ & VOC needs. CO2, RH, indoor and outdoor air temperatures, are taken as control inputs to the system while the fan speed and the ventilation door positions are control system outputs. PassivHaus Planning Package (PHPP) [14] along with EnergyPlus & GenOpt [15] were employed for concept development, detailed design and construction verification of all energy systems including the VC strategies.

When designing the systems both the adaptive thermal comfort model (when passive cooling strategies were in use, i.e. windows) and the Fanger thermal comfort model (when the mechanical system was in place i.e. MVHR) were applied to test whether the solutions were able to provide year round satisfactory indoor environments. The results showed a good potential of the proposed passive concept (highly insulated building coupled to an EAHE and exploitation of the internal thermal mass) in the selected climate, since the building is expected to have a positive yearly energy balance (local energy production exceeding energy consumption), and to guarantee high levels of comfort according to the Fanger model (Fig. 11.1).

Measured Performance

The building has undergone a long-term monitoring campaign. Figure 11.2 shows the evolution of the indoor and outdoor air temperatures during the period 4th–21st September 2015, when the building was operated in free-floating mode. We can notice that, while the outdoor air temperature reaches peaks up to 36 °C, the internal air temperature shows much smoother fluctuations, with the highest values around 28 °C. Since the MVHR was kept off during the whole period, the comfort levels were guaranteed exclusively by means of passive VC strategies, that is: the operation of the solar shading systems and the activation of the thermal mass of the building. In particular, the solar shading systems were operated manually, usually following the indications provided by the research team and by the interface of the building automation system.

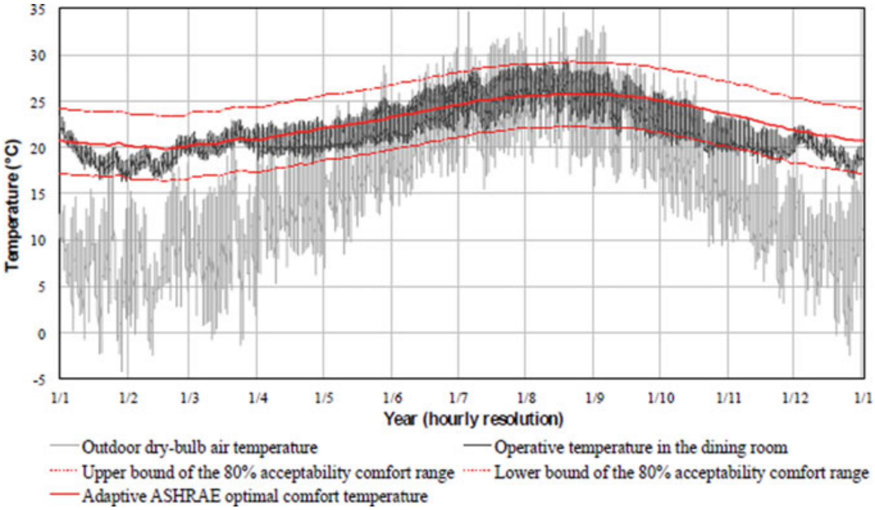

Fig. 11.1 Operative temperatures inside the living room in free-floating mode compared with the 80% acceptability range of the ASHRAE adaptive model [2]

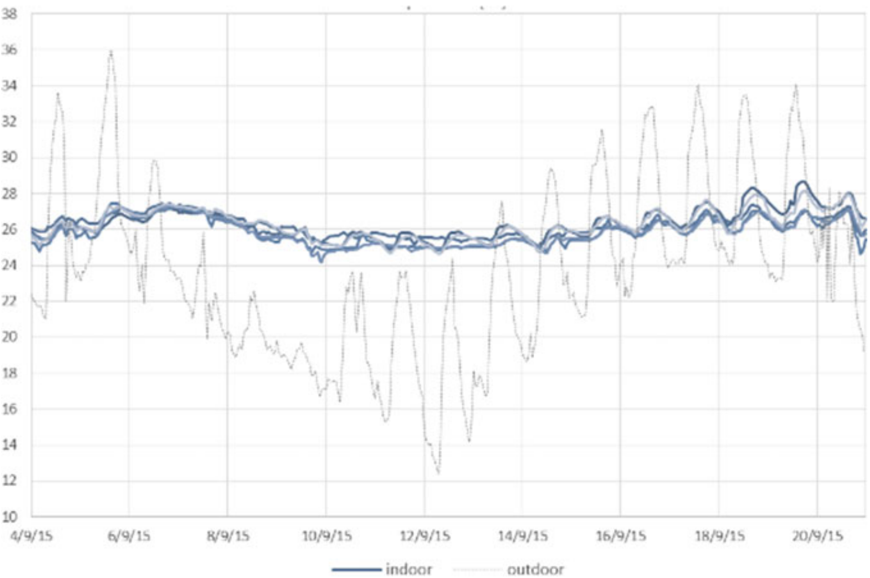

Fig. 11.2 Indoor & outdoor air temperature for measurement period 4th–21st September 2015 [2]

Overall the house has performed very well in a challenging climate for VC by exploiting complimentary strategies and a layered approach to addressing cooling needs.

11.6.2 Case Study 09—Maison Air et Lumiere (VC Strategies: NV-NC, MVHR) [16]

Maison Air et Lumière (MAeL) is a modern house in the south of Paris, as part of the Model Home 2020 project [17]. MAeL complies with the Active House principles, integrating energy, indoor comfort and the environment in the building design. The modular architectural concept pays tribute to the country's cultural heritage with its distinctive pitched roof. Pitched roofs can be adapted to meet light and solar gain needs, as well as allowing for varied interiors to suit personal preferences. The home's hybrid natural/mechanical ventilation system adjusts according to the temperature and weather conditions. This means that despite the region's warm summers, MAeL does not require air conditioning.

VC strategy

The VC strategy of MAeL was originally designed as a hybrid system, using both NV and MVHR in order to maintain the house at a good level of thermal comfort. It is also used to ensure a good indoor air quality during both winter and summer season. MVHR is preferred during the winter season, whereas NV is preferred during the summer season using the openable windows. The winter and summer season are dynamically defined on the basis of the daily mean exterior temperature, which has to be higher than 12 °C on the previous day to turn on the summer mode (redefined each day). During this period, automated façade and roof windows can be automatically opened if there are both a risk of overheating and a good potential for VC (outdoor air temperatures are great than indoor air temperatures plus an offset). This double condition can be assessed for each room of the house.

Design approach

The control strategy was originally designed to optimize VC based on indoor and outdoor temperatures. After demonstrating good performance during an initial unoccupied phase (1 year) some limits regarding its functionality and responsiveness to occupant needs surfaced once the family moved into the house: while the opening of windows was correctly synchronised with both the need for VC and sufficient cooling potential was available (outdoor temperature lower than indoor temperature) this situation of demand controlled daily variable opening schedules was not anticipated by, and confused, the family who expected to observe the same opening schedules day after day, which was not the case due to the dynamic design (same reactions were observed regarding the control strategy of external awning blinds). After a number of weeks, a decision was taken to switch to hourly-based opening

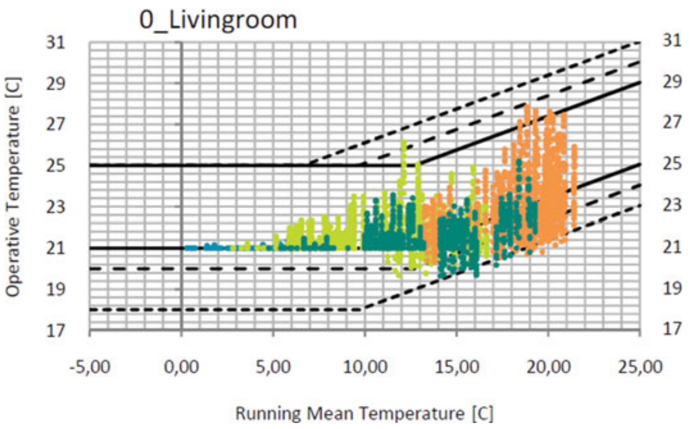

Fig. 11.3 Overheating evaluation based on EN15251 [16]

schedules in order to improve the family's perception and acceptance of the system dynamics. This new strategy was far more efficient as the family was not turning off the system as they were doing before. The project utilized BSim [18] for thermal comfort analysis and RT2012 [19] was used to demonstrate compliance with national regulations. Both single zone (bedrooms and kitchen) and multi zone (living room and mezzanine) models were developed. The design simulations were restricted to a maximum airflow rate of 5 air changes per hour. Figure 11.3 shows the results of the adaptive thermal comfort model from the simulations during the design process for the living room. The study demonstrated that there was a low risk of overheating from employing a passive VC approach.

Measured Performance

A study on the evaluation of the VC solutions employed was conducted by Ecole Des Mines in France. Field measurements of both airflow rates and indoor temperatures we conducted with data recorded for a 12 month period for indoor temperatures and a number of tests completed for airflow rates. Figure 11.4 shows the monthly spread of thermal comfort in the living room.

During the summer months, the room was in CAT1 with only a few hours in CAT2 and CAT3. In winter, the room is in CAT2 to CAT4. To obtain CAT1 in winter, the indoor temperature must be above 21 °C. The occupants themselves chose to have a temperature below 21 °C. Good agreement was observed between the simulation approaches to assessing the indoor temperatures with measurement data during a 48 h period in August as can be seen with Fig. 11.5.

The results show that thermal comfort was acceptable year round and the occupants had the flexibility to define for themselves how the VC systems were operated and what determined a good level of thermal comfort. Engagement with occupants is an important aspect to delivering successful VC in residential buildings, evident from the experiences of this case study.

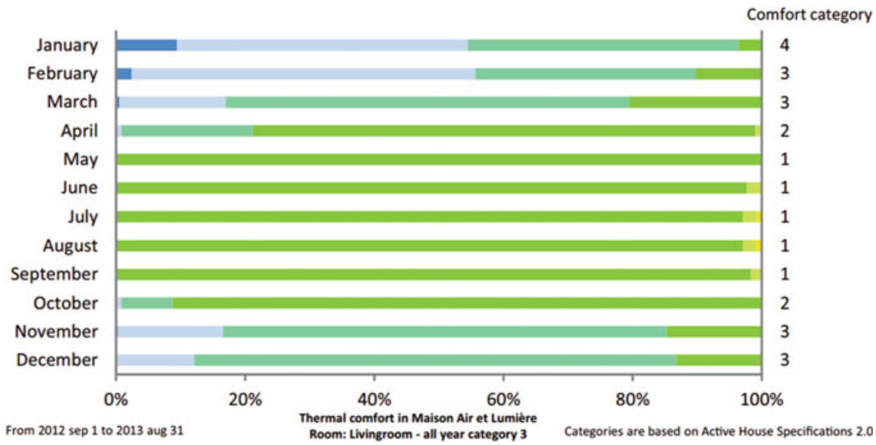

Fig. 11.4 Overall thermal sensation vote [16]

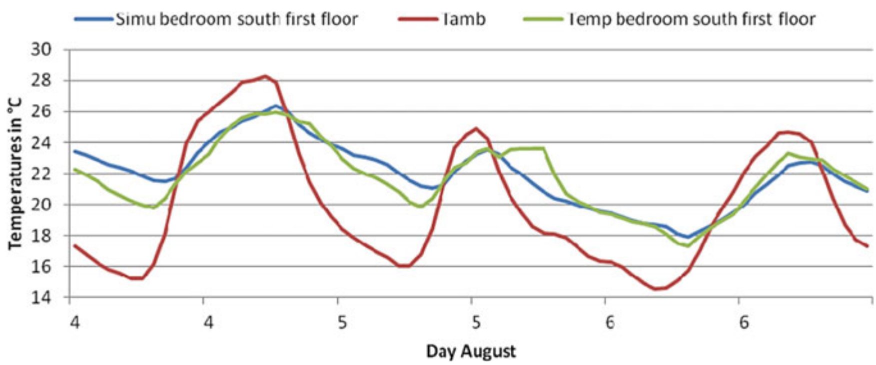

Fig. 11.5 Simulation vs field measurement for indoor air temperature for bedroom south first floor [16]

11.6.3 Case Study 11—Living Lab, Trondheim, NO. (VC Strategies: NV, MVHR) [20]

Construction of the Living Lab was completed in 2014 and first occupied in 2015. It is a 100 m^2 single family house, realized with state-of-the-art technologies for energy conservation, measurements and renewable energy source exploitation. It is planned that the building should be a test place where the heating can be supplied by space heating, radiators or ventilation and the same applies for ventilation where demands can be covered by NV only, MV only or a hybrid combination. The ventilation is designed as mixed-mode hybrid system with mechanical balanced ventilation. Supply jets are located in the living room and in the bedrooms; exhaust in the bathroom and kitchen. A heat wheel unit with nominal efficiency of 85% and an electric

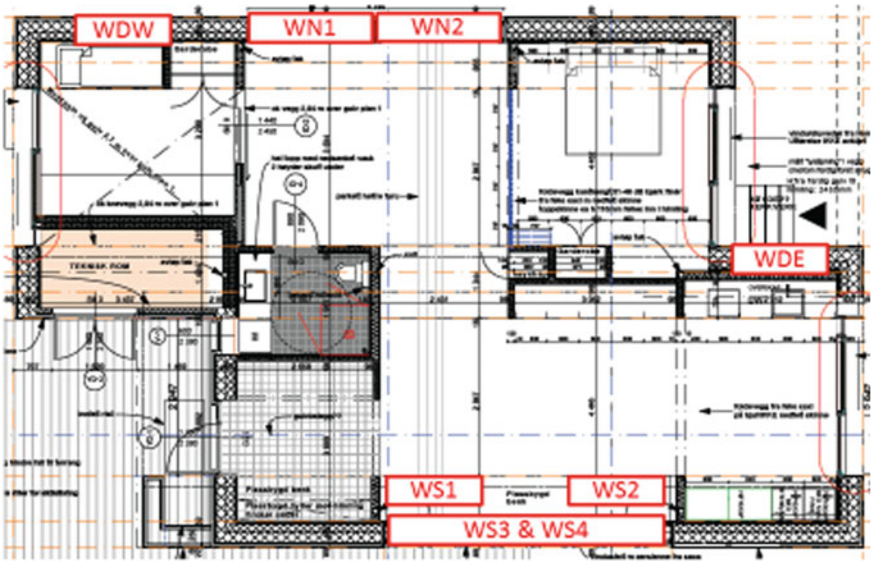

Fig. 11.6 Details of the placement of windows within the Living Lab [2]

back up coil capable of warming up the inlet air up to 40 °C are installed. It is built to demonstrate how CO_2-neutral constructions can be realized in the Nordic climate and also to conduct research on how occupants interact with the technologies in low-energy dwellings. All the windows have monitored opening and can be automatically controlled. The sliding doors in the rooms and kitchen can be opened but are not monitored.

VC Strategy

NV is available either using SSV or CV with different window combinations. The combination of the opening of WDW, WN1 and WN2 with WDE (in Fig. 11.6) provides the biggest of airflow rates as a result of the buoyancy effects. It has been observed that probably due to the triangular shape of the roof even when wind is flowing from North, the WDE placed on the higher level acts as outlet. When occupancy is present the combination WDW, WN1, WN2 and WDE with the kitchen door opening is the solution that gives the highest airflow rates. The opening of the South window does not seem to sensibly improve the cooling. During summer days with high solar irradiation, the hybrid mode is to be run with a concurrent mechanical ventilation and window opening. On the North side an oblong window is implemented. It is constructed with hinges at the top, and opens to a maximum angle of 39°.

On the West and East side there are glass sliding doors. There are two sets of rooftop skylight tripled glazed windows facing north. They open horizontally to a maximum angle of 30°. The South windows open a maximum of 37°.

Design Approach

Six control strategies have been used to determine thermal comfort and energy consumption. The opening of windows has been done in combination with mechanical ventilation. When the outdoor air temperature is too low hygienic ventilation rates are still maintained using the mechanical ventilation. For the thermal comfort, the number of hours with overheating and under cooling have been analyzed. According to the analysis of the results, the most influencing factors on the need for VC at the Living Lab were: solar radiation, outdoor temperature and occupancy. The wind does not appear to have an appreciable influence on the need for cooling, but influences the efficiency of VC. High air velocities when windows were fully open meant higher air velocities in the building. The results from the simulations implied that there will be a severe risk of overheating in Living Lab if no active or passive cooling techniques are applied. The results showed nonetheless that VC can prevent overheating without significantly increasing the energy demand. For assessing energy performance during design phases SIMIEN was employed as a simulation tool. For the evolution of performance into detailed design IDA ICE was also used. Simulations show that for years with high solar radiation, risk for overheating is happening often as a result of the high levels of building insulation. Problems with overcooling were evident from the simulation work and the proper control of windows is needed to mitigate this. The minimum measured ACR was 0.5 h^{-1} while using NV the ACR varied very much locally.

Measured Performance

Figure 11.7 shows the temperatures in the warmest place of the Living Lab for different strategies of window opening with and without mechanical ventilation. In a warm day, the cooling with only windows opening is not sufficient to reduce temperatures unless the right windows are opened. There is also a big gradient of temperatures between the North and South sides of the living room of up to two degrees for many of the measured periods with both natural and hybrid ventilation. For warm days opening the WS1 with only natural ventilation does not seem to encourage the cross ventilation and on the contrary results on increased indoors temperatures (Fig. 11.8).

In summer time, when outdoor temperatures are high, the risk for overheating and thermal discomfort is as described in Table 11.6. This table shows the results when no shading is used. In such houses, when opening the windows, temperatures are reduced.

There is normally a zone (orientation) where the sun is not shining and outdoor air is colder than indoor air. When the outdoor temperature drop and the sun is still shining there is still risk of overheating. In this case the windows opening have to be done in a controlled way to avoid overcooling. Overcooling has to be thoroughly thought in order to avoid thermal discomfort. Air velocities inside the house for only natural ventilation are measured very low between both sides of the building even when the wind speed is over 5 m/s. Further research is needed to determine the

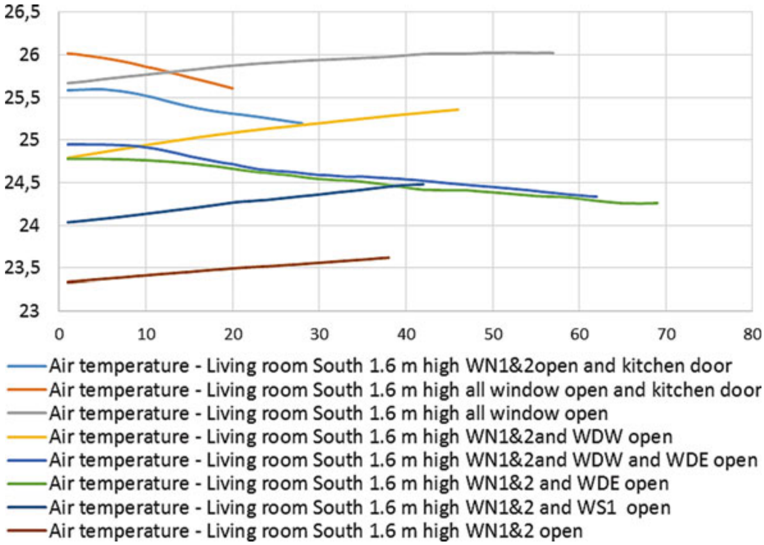

Fig. 11.7 Indoor air temperature in Southern living room with Natural ventilation as a function of time (minutes) [2, 20]

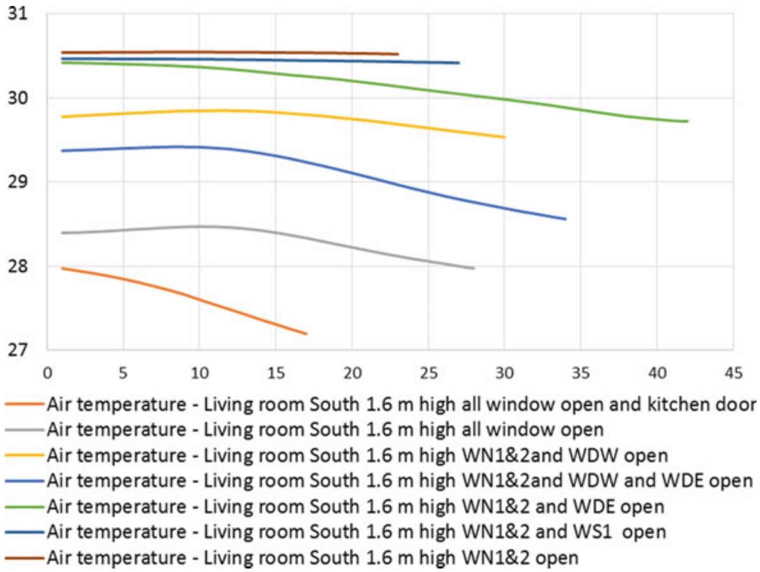

Fig. 11.8 Indoor air temperature in Southern living room with concurrent balanced and natural ventilation as a function of time (minutes) [2, 20]

Table 11.6 Effect of the window opening in the reduction of discomfort [20]

Hours of thermal discomfort					Heating and cooling energy	
Scenario	Living room [h]	Building total [h]	Decrease living room	Decrease building total	Value [kWh]	Increase compared to closed windows
No openings	105	303	–	–	126.2	–
Mech. Cooling	0	0	100%	100%	341.8	171.8%
S12.5%, N25%	17	57	83.8%	81.2%	139.4	10.5%
S12.5%, N50%	15	47	85.7%	84.5%	144.9	14.8%
S25%, N25%	15	48	85.7%	84.2%	138.9	10.1%
S25%, N50%	13	38	87.6%	87.5%	145.1	15.0%

air distribution on the building during very warm periods. Many Norwegian users want low temperatures in the sleeping room, and Fig. 11.9 shows the measured temperatures in the sleeping room for six occupant groups. To satisfy the wish for low temperatures, the low mixing rate in the Living lab seems to be very effective,

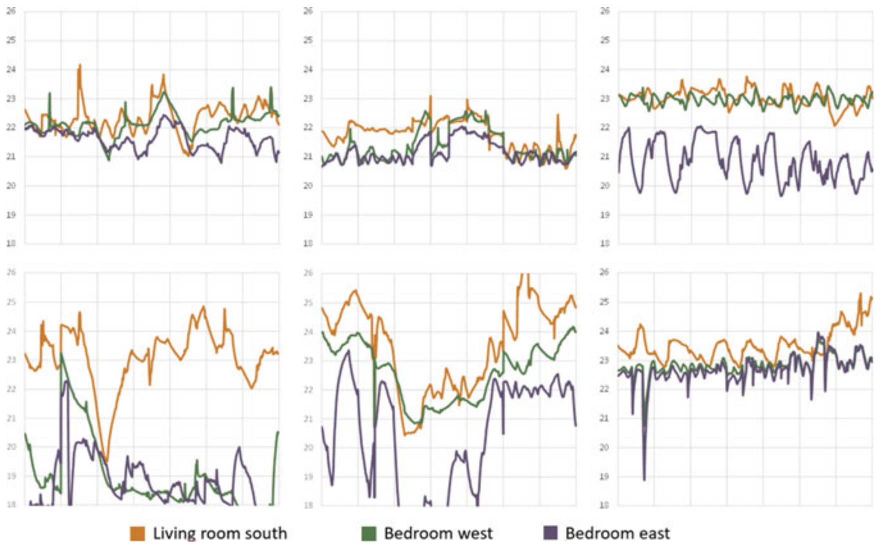

Fig. 11.9 Temperature in selected rooms during occupancy of 6 different households [2, 20]

Table 11.7 Overheating results for living lab [2]

Summer Design Values		Overheating criteria	% Occ hrs above threshold		Occ hrs
T_e	$T_{i,o}$		28 °C	25 °C	
25	26	$T_i > 26$	24	2.6	832

however, for users that want higher sleeping rooms temperatures this low mixing will result in an increase in energy use for heating. For cooling, the low mixing area ensures a cooling buffer (Table 11.7).

The Living Lab is a research facility built as a Zero Emission building. As such, the chosen solutions are not the same as those taken in a non test facility building. There are cooling demands in the Living lab when the solar shading is not used correctly and it is warm outside. In addition, based on the result for the occupancies of 6 different households, the demands and expectations vary a lot based on the user. When the house is too warm, the ventilation proves very efficient for cooling down the Living lab. By using a carefully considered window opening strategy, the cooling demands are removed. However, given the low outdoor temperatures like in Trondheim, risk for draught should never be underestimated. Protections against overcooling have to be thought through to avoid discomfort.

11.7 Conclusion

This chapter has attempted to demonstrate that there exists a wide variety of approaches for VC in residential applications, with different strategies and components available depending on the principles employed. From a review of published case studies that have been the subject of various cataloguing and/or monitoring studies simple solutions have been shown to work best, particularly those that maximize the site-dwelling interactions and dwelling morphology. Exploiting the use of Architectural features was shown to be particularly important given the low tech nature of many residences. Unlike commercial and non-domestic buildings where often solutions to cooling needs can have expert level persons responsible for their operation, in homes the users are non-technical and non-expert suggesting that the VC solutions should be simple enough to be fully understandable and operable ensuring they are not misused with the associated underperformance. Integrating the VC solutions with the architectural concept can go a long way to ensuring this. Mechanical ventilation is very common in residential properties nowadays and this can be used to enhance VC potential. When conditions are suitable Natural Ventilation is often used in combination with alternative cooling systems, particularly in warmer climates. In cooler northern climates all cooling has been shown to be available with fully passive solutions. Occupants are an integral part to a successful VC strategy for residences and working with them can improve chances of a successful cooling regime for the property. While this chapter explored VC in practice using residential case studies with proven design principles and measured performance the resilience to future overheating even in exemplar properties such as these is still a major challenge and has not been explored fully outside of research communities, with design practices not properly addressing future proofing, particularly in climates where the dominant design culture is to reduce heating consumption. There are substantial risks that houses that perform well in todays' climate will be unable to resist the increasingly hostile climate extremes envisioned in the future and in the end they may require retrofitting of mechanical cooling. The chapter has shown that VC works in residential applications but more documented case studies are needed, particularly those associated with social housing, elderly housing and high density urban residential zones that provide valuable datasets and lessons from design and building practice that can inform policy, regulations and the industry more broadly.

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Chapter 12
Ventilative Cooling in Tertiary Buildings: A School Demo-Case and Parametric Analyses Under Swiss Climate Conditions (Central Europe)

Flourentzos Flourentzou

Abstract This chapter focusses on the description of a school nearly-zero energy building (Minergie® labelled), which was designed to include ventilative cooling strategies to guarantee summer comfort conditions. This building includes a gym, classrooms, and office facilities. The gym, 11 m in height, uses a cross ventilation strategy, exploiting the strong stack effect, while classrooms and office spaces use single-sided ventilation. This building acted as reference building for the International Energy Agency (IEA) research project Annex 62. A one-year monitoring campaign was conducted to calibrate the simulations performed with the software DIAL + to carry out a parametric analysis on main variables that are able to influence ventilative cooling performances. Although, this building does not include in its final configuration a dwelling-unit for the school keeper, the architect designed a fictive apartment within the building, to perform parametric simulations. In this chapter it is, in fact, also reported a parametric analysis covering the following building usages: school, office and residential. This analysis allows on the one side analysis of the main issues influencing ventilative cooling performances, and on the other side verification of ventilative cooling resilience under climate and microclimate changes, showing very good resilience to both climate changes and heat waves.

12.1 Chapter Structure

This chapter is divided into 3 main sections: the first—Sect. 12.2—describes a real demo-case and shows how to integrate ventilative cooling issues during a design process. It focusses on the challenge of opening architectural integration and dimensioning to assure thermal comfort; the second—Sect. 12.2—introduces a parametric study, based on a reference office room retrieved from the described demo case, to analyse the thermal behaviour of a space under ventilative cooling while varying the main design parameters; the third—Sect. 12.3—is a parametric study, based on the

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same office room, that analyses the impact of climatic and microclimatic conditions, with special regards to climate changes and heat waves.

Here below the main lessons learned by the three sections are reported.

12.1.1 Lessons Learnt—Ventilative Cooling Integration in Buildings

- Natural ventilation is an efficient and sufficient cooling strategy in the central European Climate.
- Without night ventilative cooling summer comfort is not sufficient in recent highly insulated buildings.
- Night natural ventilation is the one of the most important free-cooling techniques.
- Natural ventilation in spaces with a significant height (e.g. a gym) is easy to be designed. Stack effect is, in fact, very efficient and small opening areas (4–6 m^2) may generate several ventilative air changes per hour.
- In spaces characterised by a high height, positions and dimensioning of openings determine the neutral pressure level in the building, driving where the inducted airflows come in and go out from the building, and defining where cold air enters and where heat is evacuated. Neutral pressure level is a key phenomenon and need to be correctly managed to control summer and winter thermal comfort conditions and cold draughts in winter or freshness feeling in summer.
- Automatic natural ventilation may save significant amount of money and space replacing air handling units and ducts. Architectural elements, such as windows, light wells, and doors, may become functional elements of the automatic ventilation system.
- It is a good design technique, offering interesting solutions for the architectural language, the division between glazed openings devoted to natural light, which may remain closed, and ventilation openings that might be protected, automatized, or hidden.
- Natural ventilation has a key advantage over mechanical systems in addition to cost benefits: it may give solutions to the architectural language, avoiding ducts and large technical rooms.
- Simple dynamic simulation predictions of thermal comfort, taking into account air flow and temperature dependencies based on Bernoulli's equations, are sufficient to correctly design a ventilative cooling system. Simulation predictions result to be coherent with the real building behaviour.

12.1.2 Lessons Learnt—Parametric Study Varying Design Parameters

- Solar gains is the main factor to be controlled in order to provide summer thermal comfort. Even with very efficient solar protection, highly glazed façades present significant increase of cooling needs. Partial or incorrect control of blinds may also affect seriously thermal comfort. However, a well dimensioned and controlled ventilative cooling strategy may provide summer comfort without air-conditioning. However, ventilative cooling is not sufficient to provide comfort to a fully glazed room when 2-glazed façades are present (i.e. South and West or South and East).
- The level of internal gains affects summer thermal comfort and the efficiency of ventilative cooling. Swiss norms consider the level of thermal gains as a criterion to decide the need for air conditioning. Simulations show that internal gains are a bad criterion and are not sufficient to determine the necessity to install an air-conditioning system. With natural night ventilation we may admit up to 200–250 Wh/day instead of 140 Wh/day admitted by the norm. When internal gains are an issue, it is recommended to proceed with a dynamic simulation to determine the necessity for air conditioning.
- Window size, shape and positioning determine the natural ventilation airflow. A single simple indicator according to the % of openable façade or the m^2 of opening per m^2 of floor is not sufficient as design criterion.
- Mechanical ventilation rates higher than 2-times the hygienic-required ventilation consume a lot of energy and reduce the $SEER_{VC}$ (seasonal energy efficiency ratio of ventilative cooling) to unacceptable levels, lower than standard air conditioners. The number of operational hours for mechanical ventilation needs also to be optimised to reduce this number to the strict minimum requirement (<700 h) and operate the ventilation system for night cooling during the coldest hours of the night (generally between 00:00–6:00 a.m.).
- Thermal mass plays secondary role for medium to high thermal capacity rooms. However, for low thermal capacity buildings (e.g. wooden building), is sufficient to have a screed or one massive wall to provide sufficient efficiency of night ventilation.

12.1.3 Lessons Learnt—Climate Parametric Study

- Although surface temperatures of some urban metal or mineral surfaces may rise to high levels under solar radiation, the effect of the heat island concerning air temperature variations is more significant during night that during day. This temperature rise does not affect significantly internal temperature and comfort of well-designed buildings. Day and night ventilation still remain a sufficient passive cooling strategy ensuring comfort.

- The more intense and more frequent heat waves of the last years are the prelude of climatic changes. However, a well-designed building with the right solar control and the right day and night ventilative cooling remains comfortable even considering the worse climatic change scenario.
- A sufficient, practical and easy method to test the resilience of a building to climatic changes is to simulate its behaviour with the climate of summer 2003. Using the IPCC optimistic and pessimistic scenarios we found that event without a ventilative cooling strategy, the higher cooling needs are compensated with lower heating needs. Using an adequate ventilative cooling strategy the cooling needs are reduced practically to zero.
- The answer to climatic changes and to heat waves is not a generalised use of air conditioning in the Swiss and central European climate, but a generalised and well controlled ventilative cooling technique, with efficient solar and internal gain control.
- Overheating of building elements exposed to solar radiation (blinds, double skin of a facade, decorative elements, protections of vents) or obstructing the window opening (fabric solar protection, rain or security protections of vents) create more significant overheating problems than heat island effect and even heat waves.

12.2 The Saint-Germain Primary School in Savièse—A Ventilative Building Demo Case

12.2.1 Introduction

The "Commune de Savièse" organised an architectural contest to build a small 10-classroom school building with a gym. *rk studio* proposal won the first price of the competition, proposing a peculiar unified volume, as a response to the need to integrate a contemporary modern building in a traditional preserved Wallis mountain village on the Alps. The pure line of the form imposes several serious constrains on the design of a natural ventilation system. The building was firstly designed as a typical passive building, intended to get a Minergie® label, with two distinct dual flow ventilation systems, with heat recovery: one for the classrooms and one for the gym. The gym was designed as a fully-airtight mechanically ventilated volume, while classrooms had some windows that could be opened. From the outside, the building form is in relation with its alpine environment. This relation is maintained also inside the building, through the pure form of glazed openings, framing unique fragments of surrounding landscape (Fig. 12.1, 12.2, 12.3, 12.4, 12.5 and 12.6).

The architectural language of the chosen project was coherent with the initial airtight mechanically ventilated strategy. Windows did not have any functional use. However, very soon in the design phase, the high costs of technical installation became a limit to further project development, and the necessary ducts, to bring 6000 m^3/h of air in the gym space, necessary to also ventilate up to 200 childs in the

Fig. 12.1 The considered school-demo building, composed by two joint volumes. On the left part of the picture, it can be seen the gym volume, while, on the right side, there are the classrooms. The pure line of the building is part of the architectural language defined to draw the building at the macro scale, to guarantee the wished "monolithic" form and a dialogue with the surrounding alpine environment and traditional village shapes

school canteen, which is integrated to this space, was a cumbersome element, and contrasted to the building's pure line. Cost analysis of different solutions and architectural advantages, like duct integration and reduction in space-usages for machine installations, motivated the design team to choose purely natural ventilation for the gym and mechanical ventilation for classrooms and offices. The cost of the mechanical ventilation system was around 100'000 CHF, and the duct diameter was 2 × 75 cm for the fresh air and 2 × 75 cm for the exhaust channel. Natural ventilation does not represent any extra cost, because the 4 m^2 of necessary openings on the top and bottom of the space are also required by fire protection regulations, being related to smoke evacuation. The main challenge to apply natural ventilation strategies in the gym relates to define how to integrate large openings, necessary to create a stack effect of 6000 m^3/h, in the space without changing the architectural perception.

Fig. 12.2 The pure-line effect is a desired characteristic of the building and is maintained also in indoor spaces. For example, construction details offer pure openings to frame landscape from the inside, without window-frame obstructions

12.2.2 Window Position and Dimensioning of Air Path and Flow Rate of the Gym

During summer ventilation, fresh air enters from the basement as it is shown on Fig. 12.7 and leaves the building from the top openings as it is shown in Fig. 12.8. Summer ventilation is controlled according to inside and outside temperatures. When inside temperature is higher than 20 °C and outside temperature is smaller than inside temperature, bottom and top openings open. Ventilation stops when inside temperature falls below 18 °C or when there is heavy rain or strong winds. During winter, air enters from the lateral top openings, which are positioned 2 m lower than the top front opening. The fact to make the air entering from openings situated 6 m above the floor allows the cold air to mix before reaching the occupants and to avoid cold draughts. When CO_2 concentration rise over 1000 ppm, top openings open 10%. Openings are closed when CO_2 levels fall below 600 ppm (Fig. 12.9).

Natural ventilation airflow was simulated using DIAL + software [1] to correctly dimension the openings in order to guarantee enough night ventilation for free cooling the building [2]. The position of the openings is intended. The bottom opening position in the storing room activates the concrete thermal mass of this extra space and stores coolness during night. It also avoids cold draughts because event in summer

Fig. 12.3 The assumed design solution, able to respect architect's requirements for pure glazed openings, was to dissociate air paths from light paths. The picture shows an opaque opening on the top of the space, which guarantees the evacuation of hot air from the top and avoid the creation of a hot buffer space under the roof triangles. Glazing systems on the bottom offer only light and view, without being included in the natural ventilation solution

Fig. 12.4 On the left picture, it is possible to see the building as it was on the architectural contest poster. On the right as it was realised. The only difference is the opaque windows that can be only be guessed—see for example the top of each triangular roof of the gym and the vertical façade on the right picture

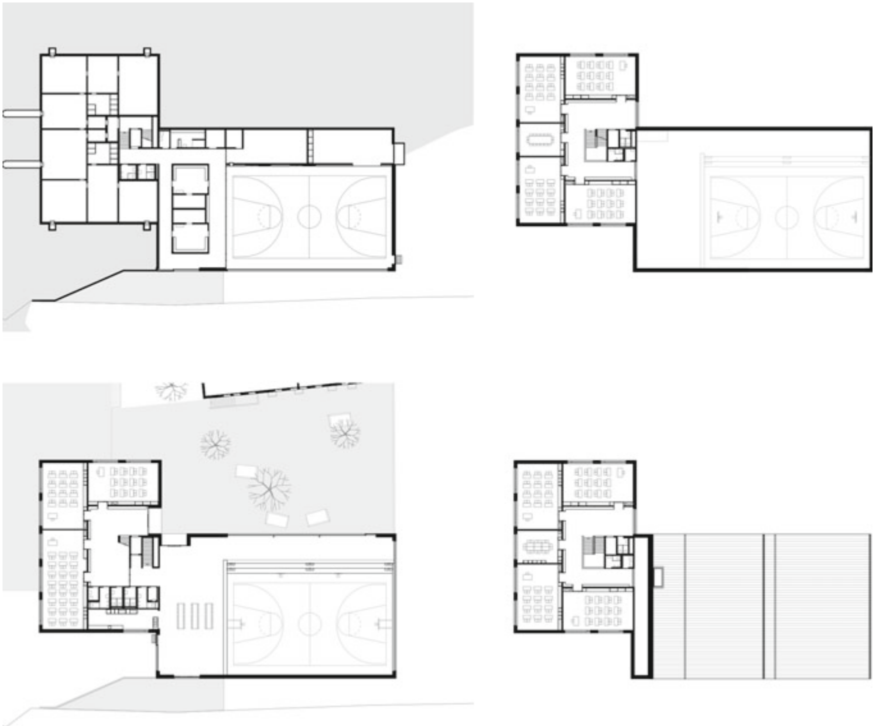


Fig. 12.5 Plans of the reference building

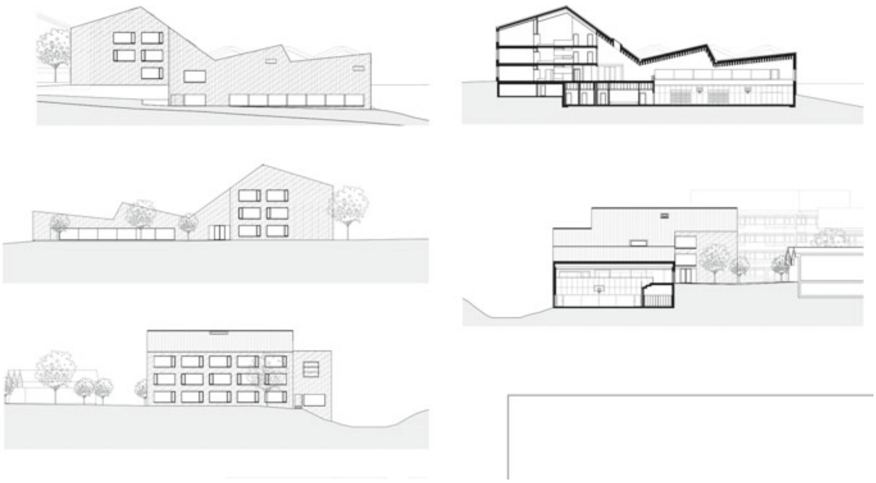


Fig. 12.6 Facades and cross sections of the reference building

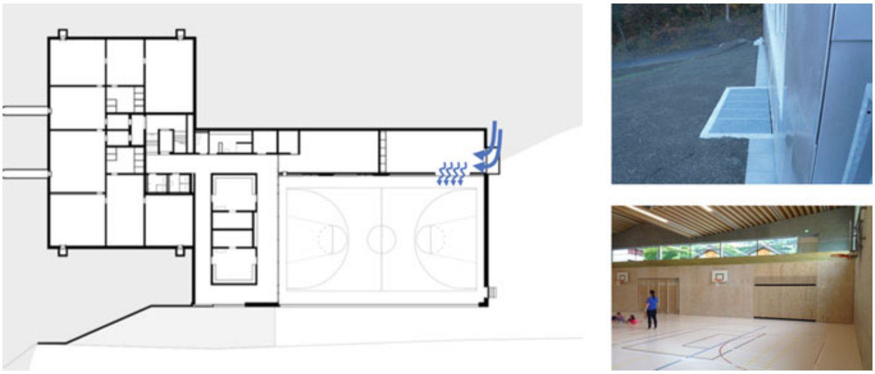


Fig. 12.7 A bottom 4 m^2 opening brings fresh air from a basement light-well situated in the storing room. Air enters through two automatic windows and passes through the perforated door that can be seen on the bottom right picture

Fig. 12.8 A top opening of 6 m^2 evacuates air on the top of the canteen (right picture) and two additional 1 m^2 openings (left drawing) allow a better distribution of air evacuation when the basement opening is open. This figure shows the night ventilation summer strategy with fresh air entering by the basement and being exhausted from the top openings

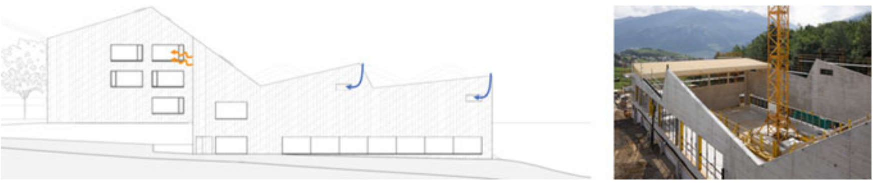


Fig. 12.9 Winter natural ventilation strategy: the basement opening is closed, and the air enters from the top lateral openings situated lower than the big 4 m^2 opening shown in Fig. 12.8. Cold air enters at 8 m in height, is mixed with hot air until it falls to the floor to avoid cold draughts. Users have not reported any cold draughts in the first-year of usage of the gym

there are fresh days that might create cold draughts. The passage of the air through a perforated wooden door was designed to create a laminar and well distributed airflow. The positioning of the automatic window in the storing room prevents children to play with it. Extra protection grids are defined to prevent children to access the automatic openings from inside, and from outside to protect from rain. Top openings prevent the creation of hot air buffer zones in the roof triangles. The big exhaust opening position on the opposite side of the air inlet assures swiping the whole space with fresh air. It is positioned on the top of the canteen space to allow the direct evacuation of pollution where the higher human concentration takes place (Figs. 12.10 and 12.11).

As it is shown in Fig. 12.10, the control of the neutral level is essential to elaborate a ventilation strategy, because it determines where fresh air enters and where exhausted air is evacuated from the building. The DIAL + images illustrate how, in summer, the main mass of inlet air enters from the bottom opening while during

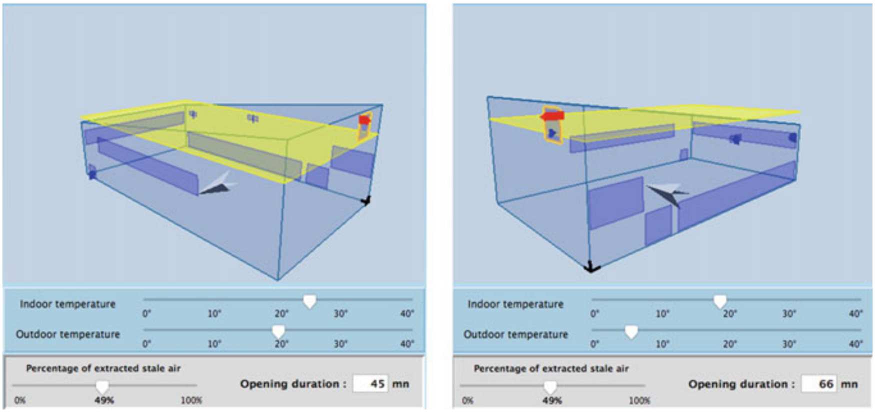


Fig. 12.10 DIAL + simulations to dimension window openings. On the left image, we can see summer ventilation with 7278 m^3/h entering from the bottom opening and 2 lower top openings under the neutral level calculated to be at 9.34 m in height when $\Delta T_{in\text{-}out}$ is 5 °C. On the right picture, we can see winter ventilation strategy. In this case the neutral level is in the middle of the top opening at 10.4 m while the airflows are 2094 m^3/h of exhaust air and 422 m^3/h of inlet air from the same opening and 1077 m^3/h + 1406 m^3/h of inlet air from the lateral top openings under the neutral level

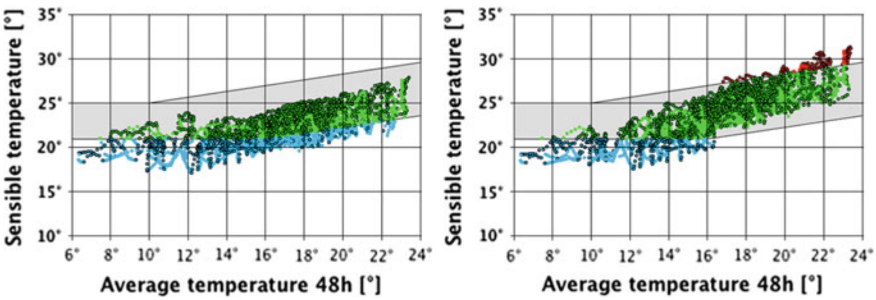


Fig. 12.11 DIAL + dynamic simulations for summer comfort. The left image shows the building behaviour with good solar control and night ventilation, remaining 2–3 °C under the upper comfort limit defined in the EN 15251 standard. The right graph shows a building configuration in which ventilation occurs only during working hours and there isn't a solar control system: the building does not comply with the comfort conditions defined in the same standard

winter it enters from the 3 top openings. By fixing the in and out temperatures in the software, it is possible to calculate the orders of magnitudes of the airflow rate. Nevertheless, detailed dynamic simulations with a coupled air/heat model need also to be used to determine if the airflow rate is enough to guarantee comfort levels, especially for the cooling strategy. The first defined strategy did not include solar control and night ventilation strategy. The adoption of dynamic simulations—see results in Fig. 12.11—showed that night ventilation and solar control are essential to guarantee building comfort conditions.

12.2.3 Window Position and Dimensioning for the Classrooms and Offices

The majority of the classrooms are West oriented. Large glazed areas (4X2 m) structure the façade rhythm. On the side of each fixed-glazed area, an openable window (0.6X2 m) enables sufficient natural ventilation during summer. For security reasons, in order to have 1 m height underside of the window, a 40 cm glazed protection was included. This protection reduces the effective opening to 0.6×1.6 m. A dual flow ventilation with heat recovery offers a ventilation rate of 5.2 m^3/m^2h according to design standards for classrooms. Night ventilation may be performed through natural or mechanical ventilation systems. The office spaces are similar to classrooms with smaller dimensions. A classroom benefits of two windows while an office room has only one window. The reference room, which was assumed for IEA Annex 62 project, is the office room in the middle of the building (indicated in yellow on the drawings below).

Outside automatic venetian blinds offer a perfect solar protection to the building according to the Swiss standards (g value <0.1). All the building concrete surfaces offer an exposed thermal mass except of the ceiling. Floors are concrete slabs with screed covered with a thin parquet flooring. Ceilings are made in exposed concrete, but a suspended ceiling hides thermal mass and avoid thermal mass activation. However, simulations in the design phase showed that the exposed thermal mass of concrete walls and floors is sufficient to reach summer comfort (Fig. 12.11).

An office room was chosen as a reference room for analyses, considering its size and position in respect to the building. It size is similar to the control room defined in the EN 13590 standard, which makes it easier to check the validity of the results and calibrate the model. The simplicity of the construction with exposed concrete walls inside and insulation outside, the shape and size of the openings, and the presence of efficient and well-managed venetian blinds make this space an ideal room to act as a reference building-space for parametric analyses.

The chosen building space was monitored during the 2015 school holidays when the school was unoccupied. It was equipped with sensors to measure air and surface temperatures on both sides of each wall, a camera that recorded the position of the blinds and window, and electric lamps that simulated internal gains according to SIA

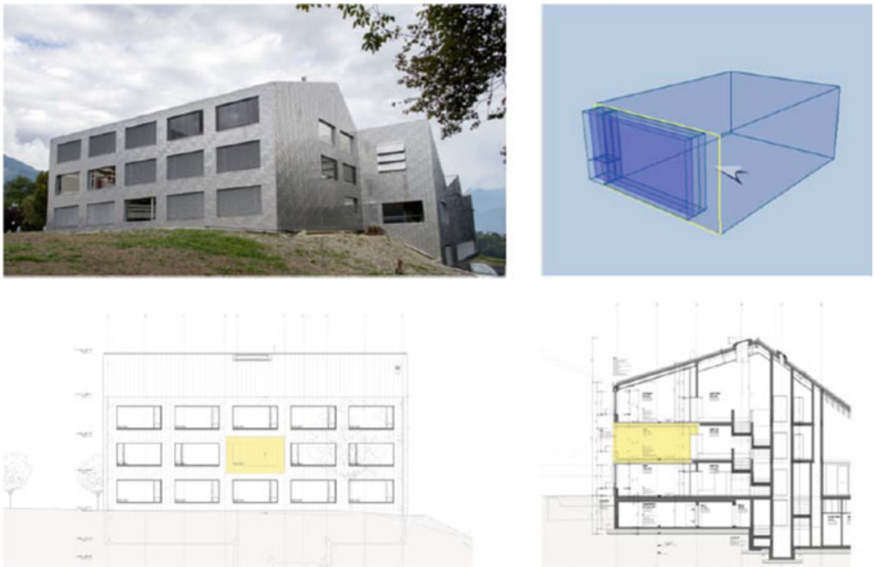


Fig. 12.12 Saint-Germain primary school in Savièse [30]. The yellow space is the one used as a reference to be modelled and monitored in order to allow a comparison between predicted and real performances

2024 technical specifications [3]. Four dynamic simulation software were used and showed coherent results with measures (EnergyPlus, LesoSai, SIA TechTool, and Dial + [1]). We used Dial + to produce the results of the parametric study.

12.3 Parametric Study Setting Ventilative Cooling Under Design Choice Variations

This section analyses the thermal behaviour of the same office room defined above by varying the main design parameters. The parametric analysis calculates comfort and energy key performance indicators for each design parameter variation in order to quantify its influence. Profiting by the calibration of dynamic simulation parameters with real measurements on the Swiss case study, we used the calibrated DIAL + to simulate the reference office, varying solar gains, internal gains, ventilation rate through the variation of the window size or position and the mechanical airflow rate and evaluate the effect of variation on comfort and energy indicators.

Hence, with a consolidated set of comfort and energy indicators [4, 5], a reference building and robust and validated dynamic simulation software, it is possible to perform a parametric analysis of ventilative cooling performances and compare them with other cooling strategies, including air conditioning.

The aim of this analysis is to use the results of Annex 62 focussing on a sample climatic and normative background—the Swiss one—to answer two questions:

– Is it possible to completely avoid mechanical air conditioning by using a ventilative cooling strategy?
– If so, what are the influencing factors, risks and limitations of this strategy?

The adopted methodology consists in taking standard conditions for 3 different uses according to SIA 2024 technical documentation [3]. Applying the thermal characteristics and ventilative cooling strategies of the reference building, we vary the influencing factors and evaluate the performance indicators. The tested ventilative cooling strategies are listed here below:

– $\mathbf{V_0}$ Standard conditions SIA 2024 without cooling ventilation
– $\mathbf{V_d}$ Optimum window opening during use ($T_e < T_i$ and $T_i > 26$ °C)
– $\mathbf{V_n}$ Optimum window opening day and night ($T_e < T_i$ and $T_i > 26$ °C)
– $\mathbf{V_m}$ Mechanical night ventilation (2.6 m^3/m^2h when $T_i > T_e + 2$ °C)

The same thermal characteristics described in the Table 12.1 are assumed, while the simulated dimensions of the rooms are those of the standard SIA 2024 rooms A office: 6.00 × 6.00, B classroom: 10.00 × 8.00 and C housing room: 5.00 × 5.00. Real dimensions of rooms are slightly different (5.00 × 7.00 for A and 10 × 7:00 for B) but we choose the standard characteristics (giving practically the same results) in order to make the results comparable to the reference indicative values (Table 12.2).

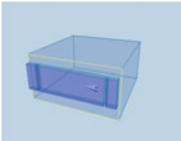
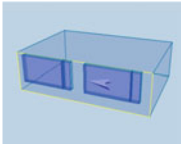
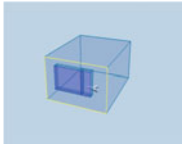
Each window measures 4.00 × 2.00 m with an opening part of 0.6 × 1.60 m for office and school use, giving an air flow rate $q_{\Delta T5°} = 337$ m^3/h per opening. For residential use, the window is adapted to 0.6 × 1.3 m in order to correspond to the standard room glazing window-to-wall ratio of 30% with an air flow rate $q_{\Delta T5°} =$ 247 m^3/h.

The daily internal gains under standard SIA 2024 conditions are 153 Wh/m^2 for offices, 266 Wh/m^2 for school rooms and 96 Wh/m^2 for housing. The Swiss norm SIA 382/1 [6] concerning ventilation and air conditioning defines the necessity for

Table 12.1 Thermal characteristics and standard building conditions

Exterior wall	U 0.2, concrete wall, external insulation	Terms and conditions of use	According to SIA 2024
Interior walls	U 2.9, exposed concrete	Hygienic ventilation rate	2.6 m^3/m^2h (SIA 2024 time schedule)
Windows	Uf 1.3, Uw 0.6 opening 0.6 X 1.2	Opening the windows	Window opening if $T_i > T_e > 26$ °C
Interior door	U 1.2	Night ventilation	If $T_i >$ Te + 2 °C and $T_e >$ 21 °C
Floor-ceiling	U 0.32 False ceiling, concrete, glued parquet	Mechanical night ventilation	5.2 m^3/m^2h 24:00 to 6:00
Blinds	Automatic slat blinds g 0.1	Blinds control	Automatic if $T_i > 22$ °C and I > 200 W/m^2

Table 12.2 Standard analysed rooms for office, classroom and housing rooms

	A. Office	B. Classroom	C. Housing
			
Dimensions	6 × 6	10 × 7	4 × 5
Glazing	50%	50%	30%
Openings	2 openings 0.6 × 1.6	2 openings 0.6 × 2	0.6 × 1.3
*$q_{\Delta T5°C}$ [$m^3/m^2/h$]	18.7	9.6	12.3
Thermal capacity	Average	Average	High
Int. gains. [Wh/m^2]	153	266	96

* $q_{\Delta T5°C}$ [$m^3/m^2/h$] is the natural ventilation flow rate when temperature difference between in and out is 5°C

air conditioning according to internal gains. Application of this simple indicator privileges air conditioning. However, in Switzerland there is another norm, determining the comfort requirements, SIA 180 [7]. This norm proposes to verify the necessity of air conditioning with dynamic simulation and takes into account night ventilative cooling. According to this norm, no air conditioning is necessary in all analysed rooms. According to [8, 9] in the majority of national regulations in Europe, night ventilative cooling is not considered. Determining the necessity for air conditioning only according to thermal gains, it does not take into account the capacity of the building to evacuate passively these gains.

As underlined in the design guide of Annex 62 [4], by performing a sensitivity analysis of parameters influencing ventilative cooling, the first parameter influencing thermal comfort is solar gains, followed by internal gains and the degree of window opening. For windy regions, whereas Switzerland isn't, wind is also an important influencing parameter. However, parameters such as the U-value of walls and roof, defined in comply with current legal requirements, do not play a role of the same importance. Based on this study, we have chosen the parameters to be modified under the Swiss weather and standard conditions of use. Before varying the parameters, we calculated indicators for the 3 most common building uses—see Sect. 12.3.1. Furthermore, as mentioned before, solar gains can be significant because of poor solar design but also because of very high window-to-wall ratio (WWR) or because of inappropriate use by the occupants in not automated spaces. These parameters are simulated to evaluate comfort and energy indicators. Three simulation cases will vary de window-to-wall ratio:

- The standard office with WWR = 50%;
- A fully glazed façade from ceiling to floor—WWR = 84%;
- Two bully glazed façades of an angular office

We will also consider a poor use of the blinds with only 50% of activation under standard office conditions with WWR = 60%. See Sects. 12.3.2 and 12.3.3.

Internal gains can also vary and this index is the second influencing factor influencing thermal comfort. In the technical documentation SIA 2024, 3 levels of internal gains and occupation levels are underlined and the same are here simulated. In this case, the degree of window opening can be a critical issue, such as mentioned before in the chapter. Therefore, in this analysis, the degree of window opening is also varied—see Sects. 12.3.4 and 12.3.5.

The last considered parameter is the thermal mass that is here analysed more in detail. We evaluated, in fact, the influence of this specific factor in collaboration with the Smart Living Lab of the EPFL where we built an experimental device with two standard rooms characterised by different thermal masses. We experimentally tested the rooms with light and medium thermal mass using earth walls or floors as mass elements. A combination of factors can create extreme situations. For example, a light room with too much glazing and a low degree of opening can lead to situations of severe overheating. Another critical combination might be low thermal mass on a building with too much glass. In this combination, thermal mass plays a different role than on a moderately glazed building where its influence is less critical. This analysis can be important for the design of wooden buildings especially with high degree of glazing—see Sect. 12.3.6.

The simulations were carried out with the DIAL + software.

12.3.1 Comfort Indicators and CRRs for Office, School Living Room Uses

The first parametric test shortly analyses the effect of different building usages of the reference standard rooms described in previous sub-sections. Firstly, the number of overheating hours according to EN 13521 standard are calculated for cases above, additionally the Cooling Reduction Ratio (CRR) is calculated—see the following expression. Results are reported in Table 12.3.

$$CRR = 1 - \frac{Q_c^{scenario}}{Q_c^{ref.}}$$

where the cooling energy needs for the ventilative cooling scenario are compared to the cooling needs for the reference fully-mechanically cooled case.

Table 12.3 Overheating hours and CRRs for the main natural ventilation strategies

	A office	B school	C housing
Default cooling requirements SIA 2024	10.8	16.9	6.5
DIAL + standard cooling requirements	9.9	11.8	6.4
Overheating hours * V_0	902	738	1909
Overheating hours* V_d	40	214	0
Overheating hours * V_n	0	34	0
CRR V_d	0.73	0.41	0.98
CRR V_n	0.92	0.69	1.00

*Overheating hours according to EN 13521 standard

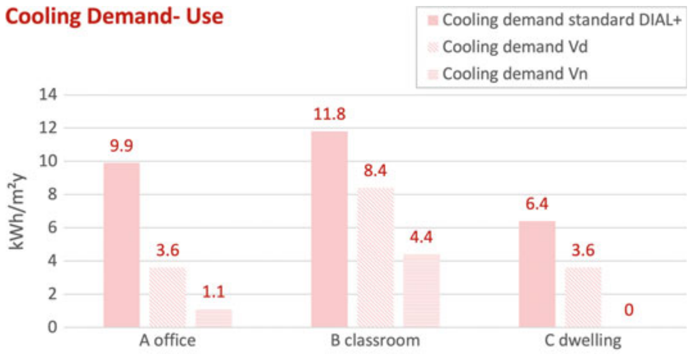


Fig. 12.13 Cooling requirements of 3 ventilation strategies for office, school, and residential building uses

As can be seen above, without opening the windows (V_0) there are between 738 and 1909 h outside of the comfort zone during the hours of use (for the dwelling case there are many more hours of occupancy) (Table 12.3).

The daytime opening strategy (V_d) drastically reduces the hours of discomfort, day and night ventilation strategy (V_n) removes almost every hour of discomfort—except for school room, where the number of people is larger and the operating temperature is at the limit of the comfort zone with few hours of discomfort (i.e. 34).

The reduction in cooling requirements is also very significant, since night ventilation eliminates practically any cooling requirements except for the school room. In addition to greater internal gains, the size of the openings (2 openings of 0.6 m × 1.6 m) is smaller. Some of the teachers in the school have made this remark (i.e. lack of air when it is hot). For this reason, one of the parameters that we are going to vary later on is the size and number of windows.

As can be seen in the graph, for the collective housing use it is sufficient to open the window and comfort is ensured.

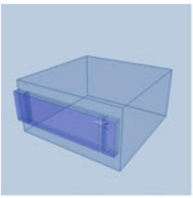
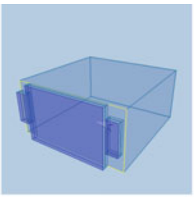
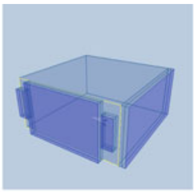
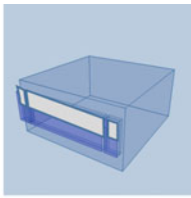
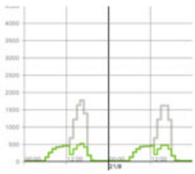
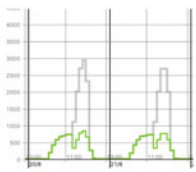
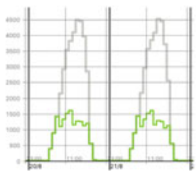
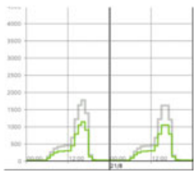
Influence of the use (school, office, residential)
• The thermal behaviour of the rooms is highly dependent on the use of the building.
• For all uses, a suitable ventilation strategy makes air conditioning superfluous.
• If day and night ventilation is not possible, daytime ventilation greatly reduces the need for cooling.

12.3.2 *Impact of the Solar Gains (Glazed Ratio and Efficiency of Blind Management)*

We have simulated the standard office SIA 2024 once with a 50% glass ratio, once fully glazed with a glass ratio of 84%, and once with two glazed façades of an angle office with 84% and 100% glass ratio. Finally, we tested the first case, 50% glazed room, with a poor blind management strategy (the blinds are half closed).

The analysis of solar gains reported in the Table 12.4 already gives to the reader interesting information that will be further expanded with a thermal behaviour analysis of the room. The room with an under-window wall reaches 500 W (14 W/m^2) in the afternoon with the blinds down. The same order of magnitude is reached in the morning with diffuse radiation gains (the window is facing west). From 1 p.m. the blinds are lowered, being blinds automatic activated as soon as the incident solar radiation exceeds 200 W/m^2. The properties of external blind solar protection used in this analysis based on technical specification 2024, with a $g = 0.14$ (protection + glazing) and triple glazing of $g = 0.5$. In the second case with a higher WWR,

Table 12.4 Glazed areas and solar gains for the scenarios simulated on 20 and 21 August

			
			
Standard awnings	1 glass façade	2 glass façades	Blinds 50%.
50% glass	Glazed 84	84/100% glass	50% glass

solar gains rise to 750 W (21 W/m^2), and with two glazed façades the gains rise to over 1500 W (42 W/m^2). With partial manual use of solar protection, which is very common in offices [10, 11], in the afternoon we have more than 1000 W (28 W/m^2) instead of 500 with the blinds closed.

As can be seen in the Table 12.5 and Fig. 12.14, solar gains are a major factor, both for thermal comfort and energy consumption for air conditioning, or the efficiency of the ventilation cooling strategy. Heat requirements rise from 9.9 kWh/m2 to 13.7 kWh/m^2 (138%) with a WWR = 84% and to 22.5 kWh/m^2 (225%) with a corner office with two glazed façades. Partial use of the blinds increases the cooling

Table 12.5 Comfort and energy indicators for 4 solar gain scenarios

	Reference Glass ratio 50%	Glazed on 1 facade 84%	Glazed on 2 façades 84/100%	Reference 50% blind closed
Hours of overheating* V_0	902	1010	1293	960
Overheating hours* V_d	40	107	591	70
Hours of overheating* V_n	0	4	367	0
Hours of overheating* V_m q_{SIA} × 1	177	460	1043	298
DIAL + standard cooling requirements	9.9	13.7	22.5	11.9
CRR V_d	0.73	0.66	0.52	0.69
CRR V_n	0.92	0.85	0.68	0.89
CRR V_m $q_{SIA2024}$ × 2	0.78	0.66	0.42	0.73

*Overheating hours according to EN 13521 standard

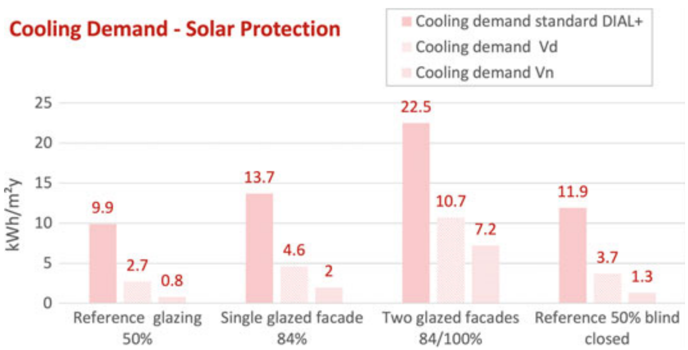


Fig. 12.14 Cooling requirements for 4 solar gain scenarios

requirements to 11.9 kWh/m^2 (120%). In terms of the effectiveness of the ventilation strategy to cool the mentioned spaces, the impact is very significant for the single 84% - glazed façade and catastrophic for the case with two - 84% glazed façades. With daytime ventilation only, comfort is clearly not guaranteed and the number of overheating hours is respectively for the two cases 107 and 591. Night ventilation barely guarantees comfort in the single 84% - glazed façade case, but shows 367 h of overheating in the two 84% - glazed facades' condition. A fully glazed office building, especially for corner spaces, would therefore be compulsorily air-conditioned in order to meet the comfort requirements. This is the only situation in where we found that night cooling is insufficient to provide summer comfort.

A corner room with two glazed façades, it is not only influenced by the mentioned solar gains thermal loads from windows, but it also has a radiative load. Both glazed façades, even with a good solar protection, show a surface temperature ranging between 27 to 28 °C instead of the 26 °C in case we had plein walls. To compensate the effect due to the warm radiation feeling, users often set the air conditioning to 24 °C (even to 22 °C) instead of the recommended standard 26 °C. This lower set temperature generates additional energy consumption.

As can be seen in the graph (Fig. 12.15), lowering the setpoint to 24 °C has disastrous effects on the energy consumption of the building. The cooling requirement for a glazed office is double in respect to the normal situation (19.7 kWh/m^2) and for the corner office is more than triple (31.9 kWh/m^2). Cooling needs exceed heating needs, and if there are no local free cooling sources (e.g. lake water), the same building will never reach a high or very high energy standard. Nor can we rely on night ventilation to drastically reduce energy consumption. As can be seen in the Table 12.4, the CRR of the over-glazed office with night ventilation is 0.68 instead of 0.92. With a setpoint of 24 °C the CRR is even lower (0.45). Additionally, the implementation of a hybrid system with air-conditioning and natural ventilation of a room with such needs becomes difficult to achieve and regulate.

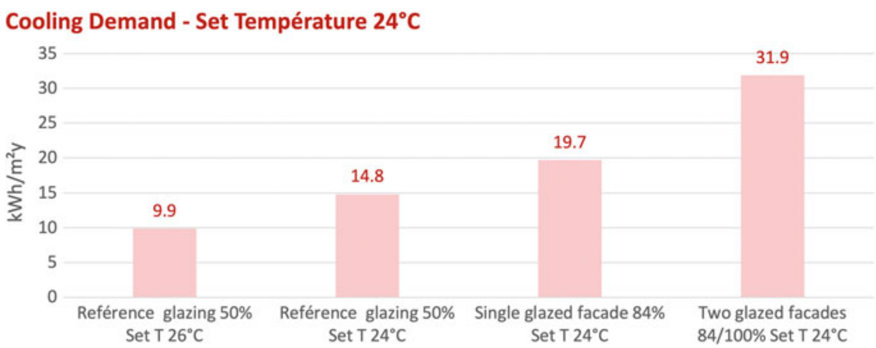


Fig. 12.15 Cooling requirements with a setpoint of 24 °C

12.3.3 Solar Gains: East and West Orientations

We have simulated the behaviour of the same rooms facing east and west. In the presence of well-regulated sun protection, the two orientations behave in the same way. While one orientation is exposed to direct solar gains that pass through the blind, the other orientation receives diffuse radiation without moderation by solar protection. The order of magnitude of the diffuse solar gains without solar protection and the direct solar gains moderated by the blind is the same—see simulation results reported in Table 12.3.

Nevertheless, a difference between the two orientations becomes significant when there is insufficient or no sun protection. This can happen in several contexts, such as when:

- buildings are old with interior solar protection,
- the solar protection control is manual, and the users lower them only partially,
- the blinds' colour is dark and they preheat the incoming air a lot in the presence of direct radiation.

We have simulated these cases with a generic simulation that takes 50% of the direct and diffuse radiation passing through solar protection. The differences in terms of annual indicators are small. However, there are days where ventilation is more effective in the east-oriented room in respect to the west-oriented case. During mooring, cool exterior air removes more efficiently morning solar gains. In the west, solar gains come when air is already too hot to remove them efficiently through natural ventilation (Fig. 12.16).

In terms of annual indicators, considering the above-mentioned strategy of solar protection having 50% of the blinds lowered, we have 11.4 kWh/m^2 of heat requirements for the east orientation instead of 11.9 kWh/m^2 for the west orientation. The CRR for daytime ventilation is 0.71 for east orientation instead of 0.69 for west orientation and the CRR for night ventilation is 0.91 for east orientation instead of 0.89 for west orientation. We have also simulated the southern orientation. With strict or automatic sun protection, thermal behaviour is similar for all orientations. With deficient protection (50% of blinds lowered), south orientation is slightly more penalised than east or west, as it is exposed to sun radiation for a longer period of time.

Influence of the glazing and sun protection
• The simulations confirm the major influence of the glazed part of the room and the management of solar gains, for summer thermal comfort and the efficiency of the ventilation strategy.
• A room with a fully glazed façade on a single side is warmer and consumes more energy for cooling. The daytime ventilation strategy is not sufficient to provide comfort, but the night-time ventilation strategy barely manages to provide it.
• A corner room with two glass facades (south and west) consumes much more energy and must be individually dimensioned for power and cooling distribution. No ventilation strategy, day or night, is sufficient to ensure summer comfort for such a room.

(continued)

(continued)

Influence of the glazing and sun protection
• Automation of blinds, which is compulsory in the case of air-conditioned building in Switzerland, is also desirable for naturally cooled rooms, especially if they are too much glazed. Overheating hours are much higher with poor blind control.
• The orientation of the room to the south, east or west does not influence the energy performance if the blinds are rigorously managed. With less strict blind control, east orientation is slightly preferable, because the cooler morning air removes more efficiently the excess heat.
• An over-glazed façade has a negative influence on thermal comfort and energy consumption for cooling in the same degree as climate change and heat waves.

12.3.4 Effect of Internal Gains

The Swiss norm SIA 382/1 states that from 140 Wh/m^2.day to 200 Wh/m^2.day, even with day and night ventilation, air conditioning is desirable, and with over 200 Wh/m^2.day it is necessary.

All simulations carried out adopt standard conditions of use defined in SIA 2024 totalising internal gains of 153 Wh/m^2.day. We have seen in the previous sections that with these conditions of use night ventilative cooling can provide comfort even for an 84% glazed room and can guarantee the comfort of the reference room even with global warming in 2060—see the following Sect. 12.4. In this paragraph we have doubled the occupancy and the heat emission of the appliances according to SIA 2024, which leads us to put 5 people in 36 m^2 (10 W/m^2), 540 W of heat by the appliances (15 W/m^2) and 572 W of gains for lighting (15.9 W/m^2). With these changes gains rise to 256 Wh/m^2.day, much higher than the limit of 200 Wh/m^2.day that SIA 382/1 sets for air conditioning rooms that may have night ventilation. The results in the following Table 12.6 show that even with 256 Wh/m^2.day of internal gains we manage to cool the reference room with night and daytime ventilation and guarantee summer comfort.

If we analyse the graph in the Fig. 12.17 we can see that doubling the occupancy/heat release increases the cooling requirements by 52%, reaching 15.2 kWh/m^2. With more internal gains, a daytime ventilation strategy evacuates more heat in absolute value (9.5 kWh/m^2 instead of 7.2 kWh/m^2 with the gains of the standard conditions) but in relative value, its CRR cooling capacity is 0.63 instead of 0.73 and the remaining hours with temperature out of the comfort zone increase to 112 h instead of 40 of the standard conditions. We have the same phenomenon with the night ventilation strategy, where although it evacuates 12.6 kWh/m^2 the CRR drops to 0.83 with 4 h outside the comfort zone. In the Table 12.6 we have produced the comfort diagram according to EN 13251 and we can see that for the reference room the points approach the upwards limit of the comfort zone, whereas with the standard gains the point cloud is much lower than the same upper comfort line.

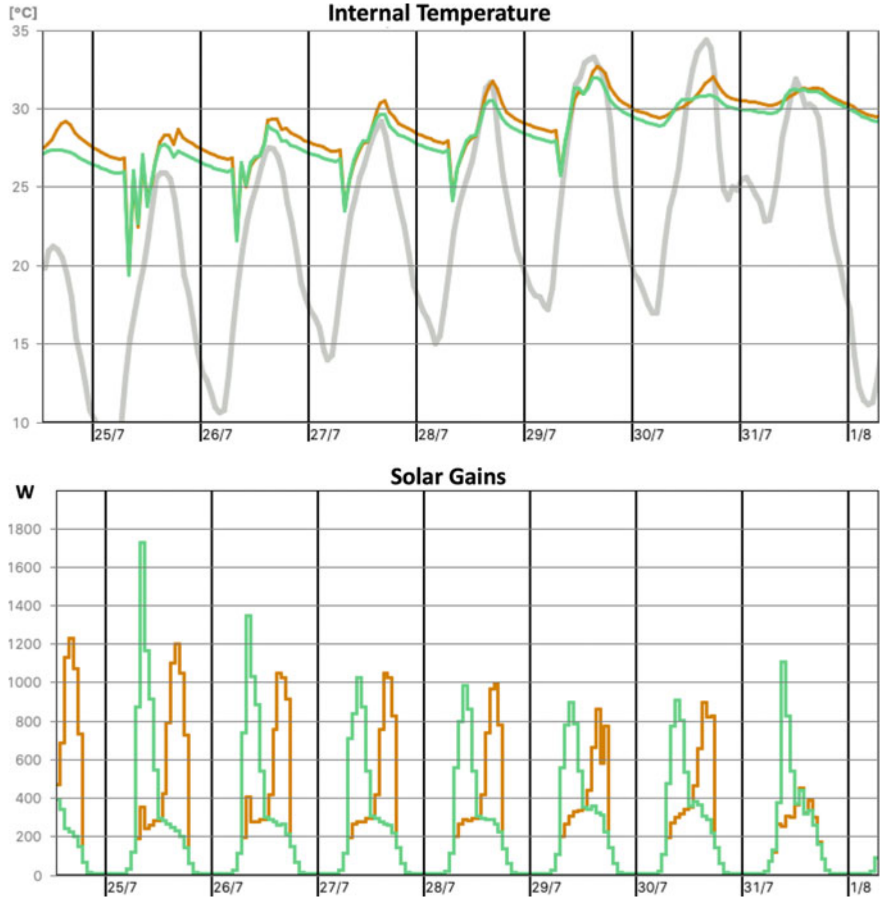
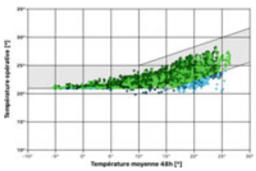
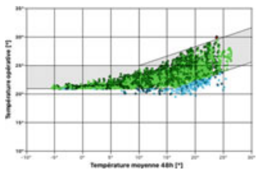


Fig. 12.16 Solar gains and indoor temperature for the reference room facing east (green) and west (red) during a hot August week

We have reproduced the table of the SIA 382/1 standard for the 50% glazed reference room with 1 m^2 of opening surface. According to the official norm, it is necessary to install air conditioning because this approach strongly underestimates the cooling potential of a night ventilation strategy, whereas it overestimate the potential of ventilation through windows during occupancy that could provide comfort with up to 140 Wh/m^2.day internal gains. It overestimates also mechanical ventilation potential providing comfort with up to 120 Wh/m^2.day internal gains. According to our simulations, in order to have zero hours of discomfort whether with a strategy of opening windows during occupation, or 24-h mechanical ventilation without opening windows, internal gains must be reduced down to 90 Wh/m^2.day. To move away from the limit of discomfort defined by the EN 13251 diagram, the internal gains must be further reduced to 70 Wh/m^2.day. These values can of course be higher with a lower

Table 12.6 Simulation results for the reference room (153 Wh/m^2.day of internal gains) and the same room with double occupancy (256 Wh/m^2.day of internal gains)

	Standard earnings—153 Wh/m^2 day	Double occupancy—256 Wh/m^2 day
Hours of overheating V_0	902	1242
Overheating hours V_d	40	112
Hours of overheating V_n	0	3
Hours of overheating V_m $q_{SIA} \times 1$	177	735
Comfort diagram V_n		
DIAL + standard cooling req.	9.9	15.1
CRR V_d	0.73	0.63
CRR V_n	0.92	0.83
CRR V_m $q_{SIA2024} \times 2$	0.78	0.58

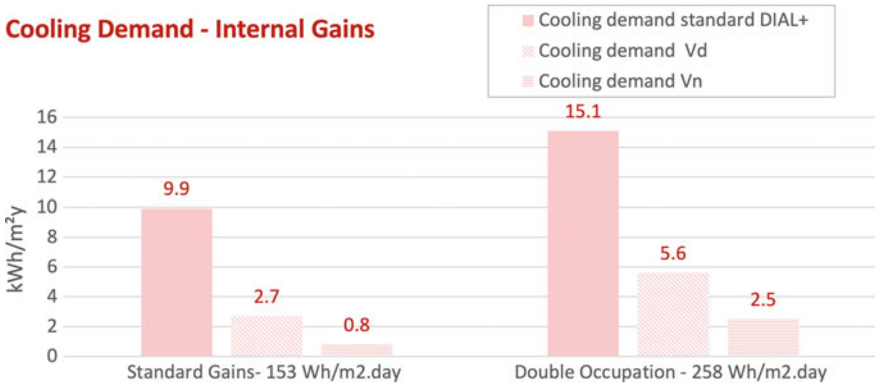
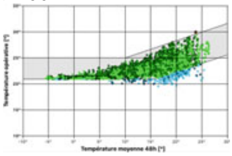
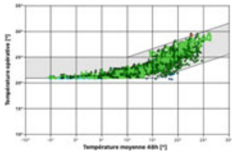
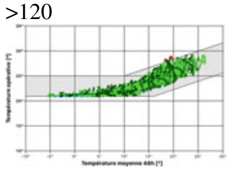
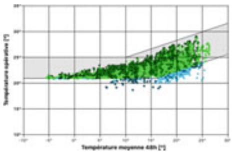
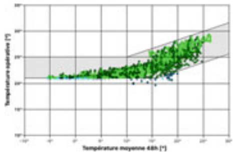
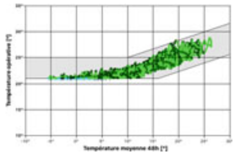


Fig. 12.17 Cooling requirements with standard occupancy according to SIA 2024 (153 Wh/m^2.day) and with double occupancy (256 Wh/m^2.day)

Table 12.7 Table from SIA 382/1 with proposed alternative limit values determining the air-conditioning requirement

	Internal thermal input Wh/m^2.day		
	Window ventilation day AND night	Window ventilation during hours of use	Without window ventilation*
Necessary	>250 >200 	>90 >140 	>90 >120 
Desirable	200–250 140–200	70–90 100–140	70–90 80–120
Superflux	<200 <140 	<70 <100 	<70 <80 

*Overheating hours according to EN 13521 standard

WWR, with presence of cross ventilation (not taken into account in these simulations), or with the use of more efficient blinds (the g = 0.38 considered in standard conditions corresponds to movable blinds positioned at an angle of 45 °C). We can retain that with internal gains higher 70 Wh/m^2.day we have to verify the comfort with a dynamic simulation.

It can be stated that, with night ventilation, the reference room can absorb up to 200 Wh/m^2.day, a value much higher than the 140 Wh/m^2.day indicated in the SIA 382/1 standard (Table 12.7).

The value of 153 Wh/m^2.day corresponds to the standard occupancy of the reference room—2.6 people for 36 m^2, internal gains of 7 W/m^2 (252 W) and 15.9 W/m^2 for lighting (572 W) with a daylight autonomy of 50%. The value of 90 Wh/m^2.day corresponds to a standard occupancy with low internal gains (3 W/m^2) and a daylight autonomy of 65%, while the value of 70 Wh/m^2.day corresponds to an occupancy of 1 person per 36 m^2, low internal gains (3 W/m^2), low consumption lighting (12 W/m^2 with 65% daylight autonomy).

Influence of internal gains
• Internal gains play an important role for summer comfort and the effectiveness of the ventilation cooling strategy, as much as solar gains.

(continued)

(continued)

Influence of internal gains
• All measures must be taken to reduce internal gains before counting to the cooling strategy: choice of appliances, occupancy density, well-dimensioned lighting with very low consumption and regulated "manual on—auto off", maximisation of daylight autonomy.
• The SIA 382/1 Swiss standard underestimates the efficiency of night ventilation and overestimates the efficiency of ventilation during occupation, whether natural or mechanical. Instead, the criteria of SIA 180 should be used to determine the need for air conditioning and be verified by dynamic simulation.
• Internal gains are not a good indicator to determine the necessity of installation of mechanical air-conditioning. A dynamic simulation taking into account the real effect of the other parameters and especially night ventilation potential is the right method.

12.3.5 Effect of Ventilation Rate

According to the design guidelines in IEA Annex 62 [4] after solar and internal gains, the factor that most influences the cooling requirements is the size of the openings. The reference room has 2 openings of 0.6 × 1.6 m, i.e. 1 m^2, with a height/width ratio of 2.6, for a surface area of 36 m^2. Windows' area is 5.5% of the floor area.

If we apply the simple criteria of summer comfort, the SIA 180 Swiss standard asks for

– a flow rate of 10 m^3/m^2h
– or mono-oriented openings >5% of the floor area if the depth of the room is ≤2.5 times the height of the room, otherwise openings in opposite walls or in corners are required.

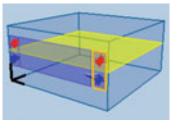
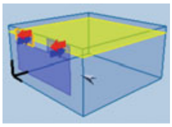
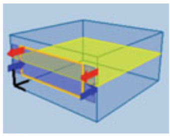
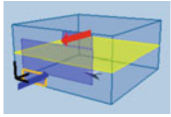
For the reference room this corresponds to a ventilation rate of 360 m^3/h and >1.8 m^2 opening area. The used openings comply fairly well with the second condition. In order to meet the first requirement, a mechanical over-ventilation of 3.8 times the hygienic ventilation is required. Given the analysis carried out when defining the $SEER_{VC}$ indicator (Seasonal Energy Efficiency Ratio of Ventilative Cooling) in [4]—see the following expression—, such a flow rate would consume a lot of electricity with $SEER_{VC}$, even 1.5 time higher than a dual flow ventilation system.

$$SEER_{VC} = \frac{Q_C^{Ref} - Q_C^{\text{Scenario}}}{E_{VC}}$$

where E_{vc} is the energy usage for ventilation.

If these ventilation rate conditions are not met, the SIA 180 requests a verification by dynamic simulation. This requirement could lead some planners to forego the night cooling strategy and use air conditioning. We will explore the possibility of reducing these ventilation rates, as well as the possibility of increasing them in cases

Table 12.8 Window layout scenarios with air flow rates at 5 °C ΔT with outside air calculated with the "Natural Ventilation" module of the DIAL + software

	Vf1	Vf2	Vf3	Vf4
				
$q_{5\,°C}$ [m^3/h]	202	410	676	1210
$q_{5°C}$ [$m^3/m^2.h$]	5.6	11.5	18.8	34.5
Min* for 50% ren.	34	25	5	4
Ratio /ref.	0.3	0.6	1	1.8

*Overheating hours according to EN 13521 standard

where the solar gains are greater than the optimal gains considered for the reference room.

We have therefore defined 6 ventilation scenarios (see Table 12.8) of which 4 correspond to different positioning or way of opening of the two windows we considered up to now.

- The first considers an opening of 30%, which would correspond to the same openings as the reference room but tilted 15 cm (15° angle).
- The second considers an opening of 60%, which would correspond to the same openings, but lying with dimensions 1.6 width × 0.6 height (instead of 0.6 width × 1.6 height of the reference room) and positioned at the same height.
- The third one is the reference room, with the two openings in vertical, 0.6 width × 1.6 height, with regular turn way of opening.
- The fourth scenario considers 180% of the flow rate of the reference scenario, with the two openings positioned 2.3 m apart (one at the top of the fixed glazing and one at the bottom). This scenario has the same openable area as scenario 2 and 3 but arranged differently. It offers 3 times more flow than scenario 2 and 1.8 times more than the reference scenario.

In the following diagram, we have used the abacus from [4] to calculate the flow rate for the vertical window 0.6 width × 1.6 height (left scale) and the horizontal window 1.6 width × 0.6 height (right scale). The relationship between flow rate and window width is linear, which is not the case for the height where we use parabolic curves (Fig. 12.18).

To calculate the flow rates for Scenario 4, with 2.3 m distance between openings, we can use a similar chart produced for the design guidelines in Annex 62 [4] or use the DIAL + software, as we have done in the following table.

As can be seen from the table above that the airflow rate varies greatly depending on the window arrangement. With the same surfaces (2 windows of 1 m^2 each,

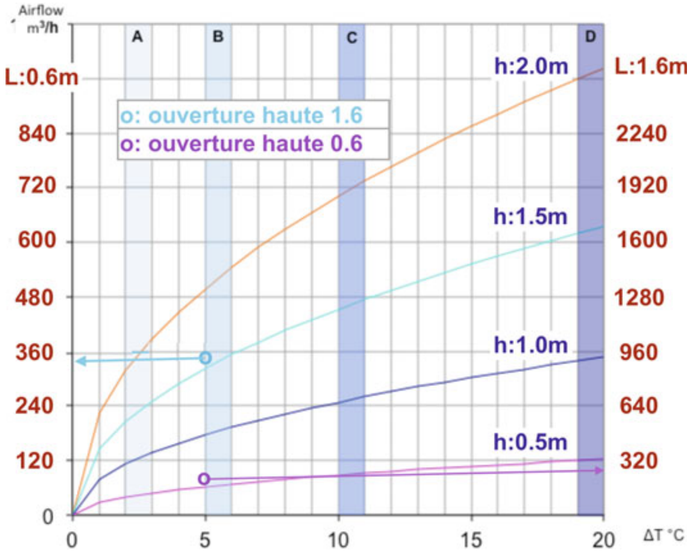


Fig. 12.18 Transformation of the scale of the abacus from [4] to calculate the flow rate of the opening positioned vertically 1.6 height X 0.6 width or horizontally 0.6 height and 1.6 width

completely open), we can obtain 410 m^3/h when the windows are layered horizontally, 676 m^3/h when they are layered vertically or 1210 m^3/h when they are separated by a vertical distance of 2.3 m from each other.

We have indicated for each configuration the time needed to renew 50% of the indoor air in the space. This information is important for the dimensioning of windows in rooms requiring rapid ventilation, such as for example, classrooms or conference rooms, which must remain closed during use and which must be ventilated quickly during short breaks.

It can be seen that the Vf1 and Vf2 configurations are not sufficient to evacuate the pollutants during a 15-min break. The same openings with more height make it possible to renew 50% of the air in the space in 5 and 4 min (Vf3 and Vf4 respectively) (Tables 12.9 and 12.10).

Table 12.9 6 scenarios of airflow variation and opening layout

The 6 airflow scenarios	
V_m $q_{SIA2024} \times 1$	Ventilation rate according to SIA 2024, i.e. 2.6 m^3/m^2h
V_m $q_{SIA2024} \times 2$	Over-ventilation flow rate 2 X the SIA 2024 flow rate, i.e. 5.2 m^3/m^2h
Vf1 ref X 0.3	Corresponds to 15 cm in tilt opening mode
Vf2 ref X 0.6	2 openings 1.6 width X 0.6 height, arranged at the same height
Vf3 ref X 1	2 openings 0.6 width X 1.6 height, arranged at the same height
Vf4 ref X 1.8	2 openings 1.6 width X 0.6 height, 2.3 m apart

Table 12.10 Comfort and energy indicators for 2 mechanical and 4 natural airflow scenarios

	Vm × 1	Vm × 2	Vf1—0.3	Vf2—0.6	Vf3—1.0	Vf4—1.8
q5°C [m^3/m^2.h].	2.6	5.2	5.6	11.5	18.8	34.5
V_d overheating hours	902	565	189	69	40	26
V_n overheating hours	177	3	0	0	0	0
CRR V_d	0.00	0.73	0.53	0.67	0.73	0.78
CRR V_n	0.58	0.79	0.86	0.90	0.92	0.93

An analysis of these results tells us that for the reference room, it is not necessary to have a flow rate of 10 m^3/m^2h to provide comfort by night ventilation as required in the Swiss norm SIA 180. It is sufficient to double the hygienic flow rate for offices. The optimisation of this flow rate is important, because a high mechanical flow rate would consume a lot of electricity and reduce $SEER_{VC}$ and consequently the ADV_{VC} of the ventilation strategy.

Sizing the windows for flow rates of the order of 34 m^3/m^2h does not greatly improve the energy performance of the night ventilation strategy or comfort. This strategy is even penalizing because it risks increasing the number of hours of discomfort (cold mornings) if the openings are not automated. On the other hand, a high flow rate through the windows improves the daytime ventilation strategy (Fig. 12.19).

In terms of cooling requirements, it can be seen from the graph above that the hygienic flow rate for night ventilation is not sufficient. A double flow rate (5.2 m^3/m^2h) improves comfort for both day and night ventilation. The optimisation of this flow rate, on the other hand, must take into account the performance of the mechanical ventilation system, by calculating the $SEER_{VC}$ and ADV_{VC} and compare to an air conditioning system.

For natural ventilation performance, it can be seen that with only 1.6% of opening surface area (in relation to the floor area), this is sufficient for night ventilation

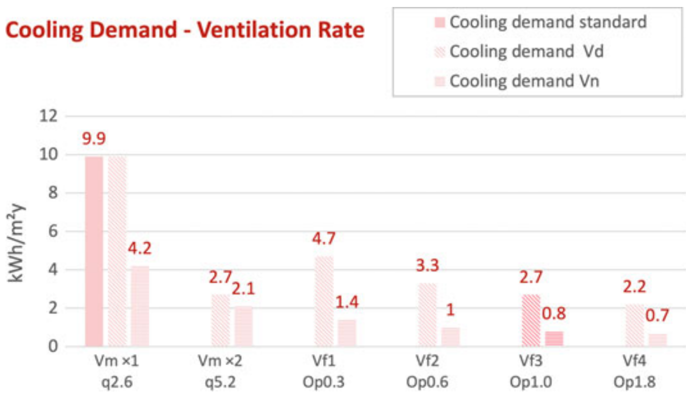


Fig. 12.19 Cooling requirements for different flow rates and arrangement of openings

(scenario Vf1). On the other hand, higher degrees of opening are beneficial for daytime ventilation ($\geq$5%).

A good solution could be to be able to open them 100% manually in regular turn mode during the day when necessary and partially in tilt mode (manually or automatically) during the night. Another solution, which is very appreciated by users, is to split a vertical window into two and have a manual mode in the lower part to open during the day when desired, and an automatic mode in the upper part for the night. This system is also convenient for security issues.

Influence of the mechanical ventilation rate
• The hygienic flow rate of 2.6 m^3/m^2 h is not sufficient for either day or night ventilation, although it does improve the situation.
• A double flow rate (5.2 $m^3/m^2 \cdot h$) is sufficient but the flow rate of 10 $m^3/m^2 \cdot h$ suggested by the SIA 180 standard is excessive.
• When this system is chosen for cooling, the $SEER_{VC}$ should be checked to have at least a value >4 (a bad split air conditioner) and an $ADV_{VC} > 1$.
• The $SEER_{VC}$ must be optimised by optimizing the number of night ventilation hours (less than 700 h of night over-ventilation—a priori 6 h per night) and to centre the operating hours around the coldest hour of the night.
• It must be checked that the system's operating speed in over-ventilation mode for cooling is within an optimum operation range of the air handling unit.
• In the actual reference room, we observed a warming of the air in the distribution network of the dual flow ventilation embedded in the slab, resulting very small temperature variations.

Influence of the natural ventilation rate
• An openable area ~2% of the floor space is sufficient for night ventilation (one 1 m^2 window opening for 20 m^2 of office space open tilted).
• An openable area ~5% of the floor space is optimal for ventilation during hours of use (a 1 m^2 window for 20 m^2 of office space open regular turn completely).
• Prefer high openings and avoid low longitudinal openings.
• If the architectural style of the windows imposes low height (<1 m) longitudinal openings, make sure to have two opening windows with at least 1 m distance between them in height to create higher stack effect than the window height.

12.3.6 Effect of Thermal Capacity

The reference office is made with an "average" thermal mass according to the SIA 180 classification. This corresponds to the following characteristics: concrete floor + uncoated screed with thermal resistance, false ceiling and two external concrete walls (with external insulation) not exceeding 80% of the floor area (Fig. 12.20; Tables 12.11 and 12.12).

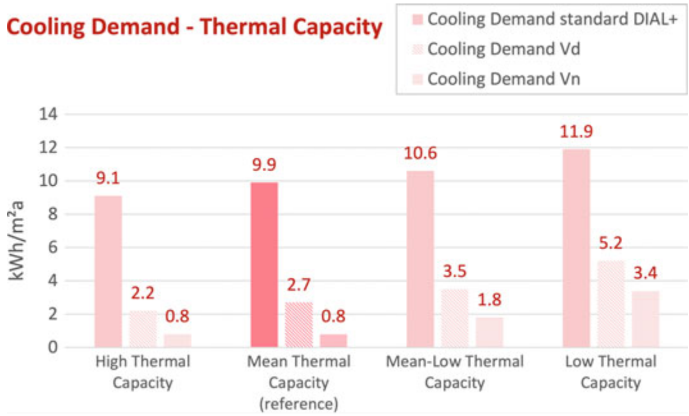


Fig. 12.20 Cooling requirements associated with the three ventilation strategies as a function of the 4 levels of thermal capacity

Table 12.11 Heat capacity according to SIA 180

Heat capacity according to SIA 180	
High heat capacity	Exposed concrete floor or ceiling, + additional concrete surfaces totalling at least 80% of the floor area. The other surfaces are light partitions or suspended ceilings—raised floors.
Average heat capacity	Concrete ceiling or floor with at least a 6 cm thick mineral screed, including the covering if mineral and the other walls in light partitioning with a wooden construction or similar.
Low heat capacity	Lightweight construction (timber construction, steel structure) with lightweight partitions.

Analysing the results of the table and graph, we can see that the impact of thermal mass is quite particular. The cooling requirements do not increase dramatically. Even for the room with a low thermal capacity they only increase by 2 kWh/m^2a (20%) compared to the reference room. The room with high thermal capacity reduced cooling requirements only by 0.8 kWh/m^2a (−8%). On the other hand, the efficiency of the ventilation strategy is more affected by the thermal capacity, especially for the lower values. We can see this in the variation of the CRR, both for day and night ventilation.

It is also interesting to observe how low thermal capacity affects more negatively the cooling efficiency of a low ventilation rate strategy (the V_m mechanical ventilation CRR) (Fig. 12.21).

The impact of thermal capacity on ventilation efficiency is more visible on the comfort indicator. The room with a high thermal mass ensures almost constant comfort (11 h outside the comfort zone) while the room with a low thermal capacity shows 187 h of overheating with the same strategy. Rooms with medium-low and

Table 12.12 Simulation results of comfort and energy indicators with different levels of thermal capacity

	High thermal capacity	Average heat capacity (reference)	Medium-low heat capacity	Low heat capacity
Hours of overheating V_0	830	902	918	971
Hours of overheating V_d	11	40	81	187
Hours of overheating V_n	0	0	10	89
Hours of overheating V_m	110	177	303	514
DIAL + standard cooling requirements	9.1	9.9	10.6	11.9
CRR V_d	0.76	0.73	0.67	0.56
CRR V_n	0.91	0.92	0.83	0.71
CRR V_m	0.85	0.78	0.66	0.45

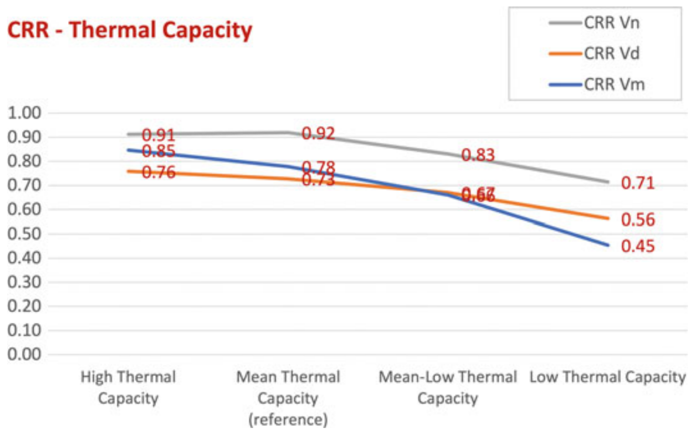


Fig. 12.21 CRR of three ventilation strategies (Night and Day Ventilation V_n—grey, Day Ventilation V_d—red and Mechanical Ventilation V_m—blue) for 4 levels of thermal capacity

low thermal capacity do not ensure comfort under normal conditions even with night ventilation.

A low thermal mass therefore has a greater influence on extreme temperatures than on the average behaviour of the room (cooling requirements without a ventilation cooling strategy). The small effect of thermal mass on average behaviour and the higher sensitivity to extreme conditions has also been observed by other authors [14, 29]. What is interesting to observe, is that a simple screed (medium-low thermal

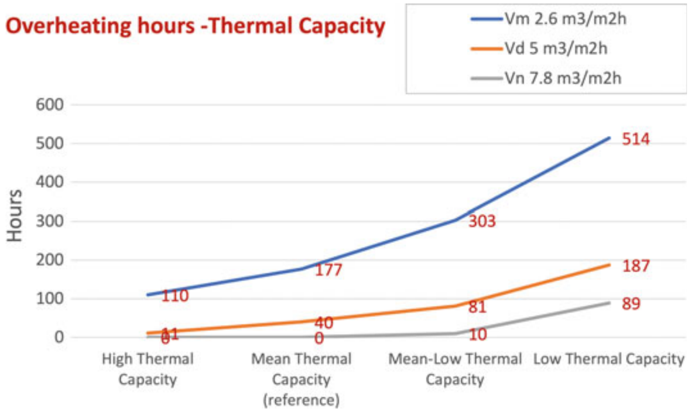


Fig. 12.22 Overheating hours of 3 fan cooling strategies for 4 levels of thermal capacity

capacity) is sufficient to have a very significant effect in ventilation efficiency. This is important for timber and other lightweight constructions where a simple and not expensive architectural choice brings enough thermal mass to make the building thermal response to night cooling more efficient (Fig. 12.22).

As can be seen in the graph above, a room with a low thermal capacity and 50% glass cannot ensure summer comfort under normal conditions of use, even with night-time ventilation (89 h of overheating). With daytime ventilation only, the situation is worse with 187 h of overheating, which is not acceptable. As we can see in the graph, the room with low thermal capacity becomes very sensitive to heat. It is worth exploring this case further, with more and less solar gains, and with different levels of low thermal mass.

12.3.7 Behaviour of the Reference Room with Low Thermal Capacity

For this specific case, we collaborated in this project with the Smart Living Lab (SLL) of the EPFL. The SLL realized an experimental device with two identical offices, one with very low thermal mass (all walls and ceilings with wooden sandwich panels with 18 cm of polyurethane insulation). We varied the thermal mass of the floor with a cement screed, and a wall with compacted mud bricks. We measured the behaviour of the room in order to calibrate the parameters of the DIAL + software, and then we simulated the same ventilation strategies as for this parametric analysis and with 5 variants of low thermal mass. The room is located in Fribourg, with a cooler summer weather than Geneva, and the solar protections of the room are better than the standard values of SIA 2024. The detailed results of these studies are published in [13, 15]. With these small improvements in the standard conditions (g of the blinds,

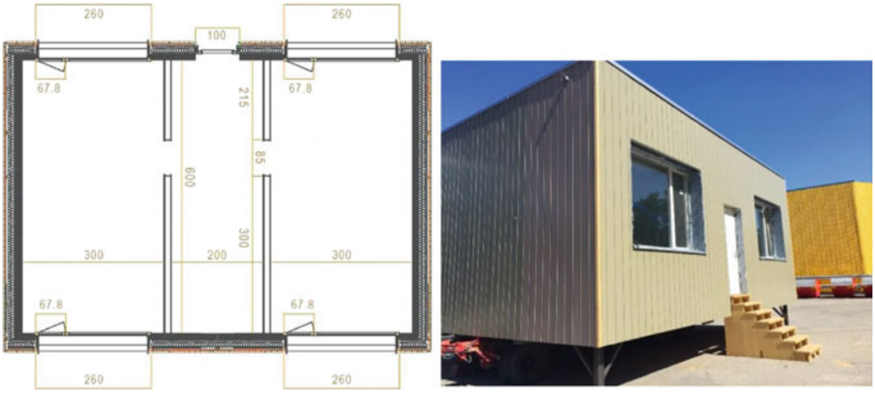


Fig. 12.23 Experimental test room for the study of heat capacity at the Smart Living Lab. One of the 2 rooms has a low thermal capacity and the other is equipped with a raw clay screed and/or a raw clay brick wall

weather in Fribourg, form factor of the room with more walls per m^2 of floor), the experimental room with low thermal mass has only 25 h of discomfort instead of 89 h for the standard SIA 2024 room in Geneva. By adding a simple raw earth screed, these hours of discomfort are reduced to 4. This sensitivity of rooms with low thermal capacity underlines the need for a more careful design, with verification of the choice of glazing, blind properties and thermal mass by simulation (Fig. 12.23).

As thermal capacity has less influence on the thermal behaviour of the building than solar or internal gains, especially with an efficient natural ventilation strategy, the SLL looked at the real energy benefit by taking into account the grey energy that becomes important when concrete is used to increase thermal capacity. As the differences between high and medium capacity are small, the environmental impact (primary energy, CO2 equivalent) of concrete is greater than the energy benefit.

The results of the life cycle assessment therefore show that the average thermal capacities (S3, S4) are globally the most interesting, especially if the thermal mass is provided by natural materials with low carbon impact and low grey energy, as is the case with compacted raw earth [13–15].

Behaviour of timber construction

In view of the importance of the results of the study in the previous paragraph and taking into account the complexity and sensitivity of the dynamic behaviour of a light room, we have specially analysed the behaviour of a wooden room for the standard conditions of use and the climate of Geneva. We would like to answer the following questions:

1. Is at least a screed or other heavy element absolutely necessary in a wooden construction?
2. Can an optimised timber construction withstand a heat wave or cope with climate change?

Table 12.13 Overheating hours and maximum operating temperature of the experimental room in Fribourg as a function of its thermal capacity

Construction of the premises	SIA 180 classification	Hours of overheating	Maximum temperature [°C]
S1. Wood—Polyurethane	Light	25	31.3
S2. Wood + plaster	Light	9	30.7
S3. Cement screed	Low average	4	30.1
S4. Clay bricks	Low average	0	28.7
S5. Clay screed and bricks	Average	0	28.2
S6. Concrete	Important	0	26.9

In order to answer these questions, we have further optimised the other sensitive parameters other than thermal mass for variants S1 and S3 in the Table 12.13. We have thus chosen:

– A more efficient lighting system with 12 W/m^2 instead of the 15.9 W/m^2 of the standard variant.
– Very light colours on walls, floors and ceilings to increase daylight autonomy to 57% for 500 lx, 76% for 300 lx or 81% for 500 lx in the main use area (4 m deep) (we took 76% autonomy in the calculation).
– High-performance exterior movable blinds with a g-value of 0.15 instead of 0.28 specified in the SIA 2024 standard conditions.
– For S3, we created an "optimisation 2" by reducing the glass surface to 30% instead of 50% of the reference room in addition to the other improvements.

This last optimisation not only reduces solar gains, but it also reduces daylight autonomy and therefore increases internal gains. According to a simulation with DIAL + , the average autonomy for a 500 lx lighting level drops from 57 to 37% and for 300 lx from 76% to 64%. If we consider the autonomy at 500 lx in the area of main use, we go from 81% to 53%. We took an autonomy of 76% in optimisation 1 and 53% in optimisation 2. Although the solar gains are lower for optimisation 2, the internal gains are higher with a lower autonomy, which gives lukewarm results (Figs. 12.24 and 12.25; Table 12.14).

As we can see from the table, although the cooling requirements are drastically reduced (6.4 to 7.4 kWh/m^{2}a instead of 9.9 for the reference room), there are still hours of residual overheating, and even with night ventilation, we have respectively 47 and 36 h out of the comfort zone for the room with low optimised thermal capacity. Only the room with screed (medium–low thermal capacity) guarantees comfort when it is optimised. Unfortunately, optimisation 2, although it reduces solar gains, increases electricity consumption for lighting, so this optimisation is not interesting.

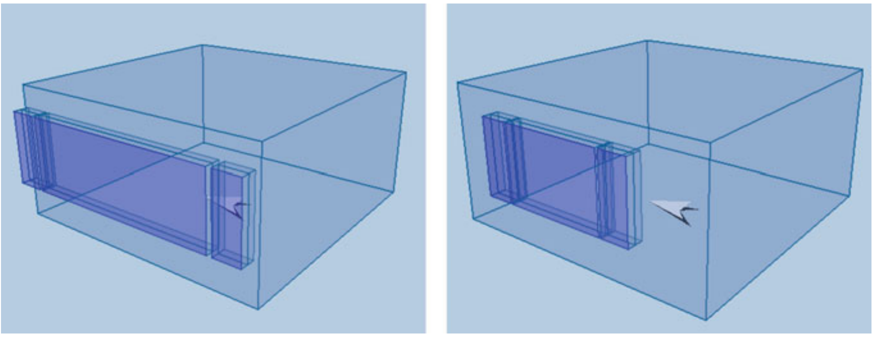


Fig. 12.24 Glazing of the reference room (and of optimisation 1) and optimisation 2 with the glazed surface reduced to 30% of the façade instead of 50% of the reference room

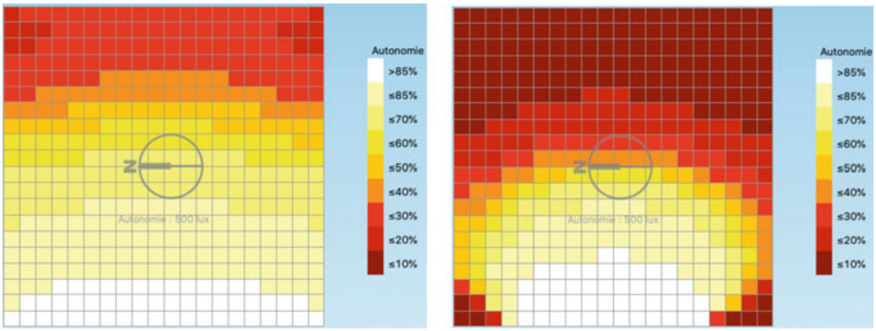


Fig. 12.25 Daylight autonomy of the two rooms (DIAL + simulation)

So, the answer to question 1 is that without a screed or other element with thermal mass, the comfort without cooling for a wooden desk with a wooden or metal structure is critical. With the low number of overheating hours for the optimised room, it would be possible to guarantee comfort with a ceiling fan, or with underfloor geothermal cooling of 10 W/m^2 without a cooling machine.

We simulated the optimised room with screed and found only 9 h of overheating on the hottest summer days. As we can see from the following weather diagram, these few hours of discomfort take place in June and August, which correspond to the weather in summer 2003 according to Meteonorm's max file. So, the answer to question 2 is yes (Fig. 12.26).

A building that can withstand heat waves is also a building that will withstand climate change, at least until 2060, as we will see in the following paragraphs.

Table 12.14 Comfort and energy indicators for optimised low thermal capacity rooms

	Average heat capacity (reference)	Medium-low th. capacity—optimised premises	Low th. capacity—optimised room 1	Low th. capacity—optimised room 2	Low th. capacity—non-optimised room
Hours of overheating* V_0	902	667	673	889	971
Overheating hours* V_d	40	43	95	80	187
Hours of overheating* V_n	0	0	47	36	89
Hours of overheating* V_m	177	72	253	212	514
Standard cooling requirements	9.9	6.4	7.4	7.1	11.9
CRR V_d	0.73	0.67	0.58	0.61	0.56
CRR V_n	0.92	0.84	0.72	0.73	0.71
CRR V_m	0.78	0.70	0.49	0.54	0.45

*Overheating hours according to EN 13521 standard

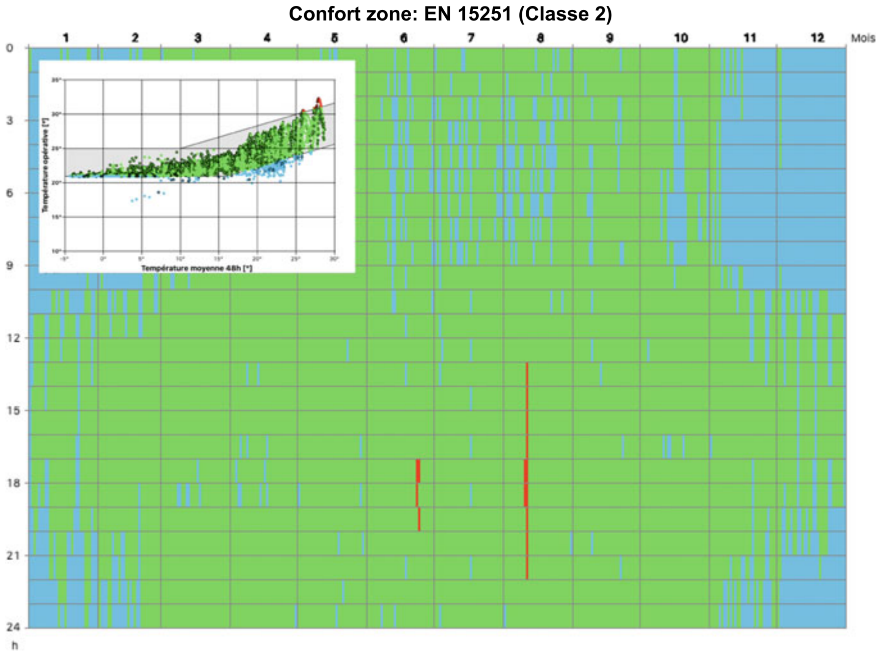


Fig. 12.26 Time diagram for a wooden building in Geneva with optimised solar gains and a screed on the ground, for a year with strong heat waves in June, July and August (as in 2003)

A wooden construction, therefore, requires special design attention in order to offer it a little thermal mass (a screed or a solid brick wall), good blinds and good natural light autonomy.

In addition, we simulated a light room with 84% glass surface. With night-time ventilation, comfort is barely guaranteed (14 h of overheating) for an average year, but such a light, glazed room would not be able to withstand heat waves without additional cooling. The 43 h of overheating already appear in the month of March with perfect solar protection management, and become 151 with poor blind management (Fig. 12.27).

Influence of the thermal capacity
• The influence of thermal capacity is low for a well-designed room from the point of view of solar protection, reasonable internal gains and intelligent ventilation..
• The influence is also small for mechanically cooled buildings.
• Thermal capacity is important for extreme conditions (heat peaks) where the total absence of massive elements becomes critical. A non-optimised room without thermal mass requires cooling.
• A light wooden office building can offer comfort without air-conditioning, provided that the blinds, night ventilation are perfectly managed and at least a single element of average thermal mass (screed or solid brick wall) is present.

(continued)

(continued)

Influence of the thermal capacity
• A light wooden office building, without a single element of medium thermal mass can offer comfort with a light floor cooling with 10 W/m^2 of geothermal cooling or with ceiling fans, buried pipe ventilation or adiabatic cooling of 10 W/m^2, provided that the blinds and night ventilation are perfectly managed.
• Too much thermal mass does not provide an energy added value that compensates for its grey energy or CO2 impact. If it is present for constructive reasons, it must be preserved, but it is not necessary to impose it for comfort or energy reasons.
• An average thermal mass is a good compromise between grey energy and summer thermal comfort for a wooden light construction.
• A low thermal mass is good for grey energy, but the total absence of thermal mass makes the building sensitive and requires perfect control of the blinds and night ventilation.
• The combination of low thermal mass (even with screed and optimum design) with a high proportion of glazing makes the building sensitive and the building control system or occupants have no room for error.

12.4 Ventilative Cooling Parametric Study for Climate and Microclimate Variations Under Swiss Climates

Parametric studies in bibliographic references analyse ventilative cooling mostly for buildings built before 2010. Near zero energy buildings, which are more and more the common case today, and the buildings designed according to new regulations have very different thermal behaviour in respect to traditional buildings. High level of external insulation is generally required in all European countries, even the most southern regions. A 6–10 cm insulation on a building in southern countries creates a completely different thermal behaviour also in summer conditions. In the central European climates, the minimum insulation thickness is 16–20 cm, and high-performance envelopes have 25–32 cm insulation. Air tightness and high-performance double or triple glazing are also removing any dissipative possibility of the buildings that become very sensible to solar and internal heat gains. In Switzerland solar gain control is compulsory in the last 20 years and changed the architectural landscape of the country. However, this regulatory situation is far to be the rule in Europe, even for the hot countries where glazing is more exposed to sun. The parametric analysis of ventilative cooling is different under solar control conditions or not. The higher overheating risk comes from the sun and not from outdoor temperature, especially in central and north European climates.

This section analyses the climate and design parameters for this type of constructions and conclusions may be in some cases different from the analysis on the traditional buildings in past research. Traditional buildings for example in Central Europe could operate with reasonable degree of discomfort without night cooling. With the new construction regulations, with high insulation levels, high airtightness, summer

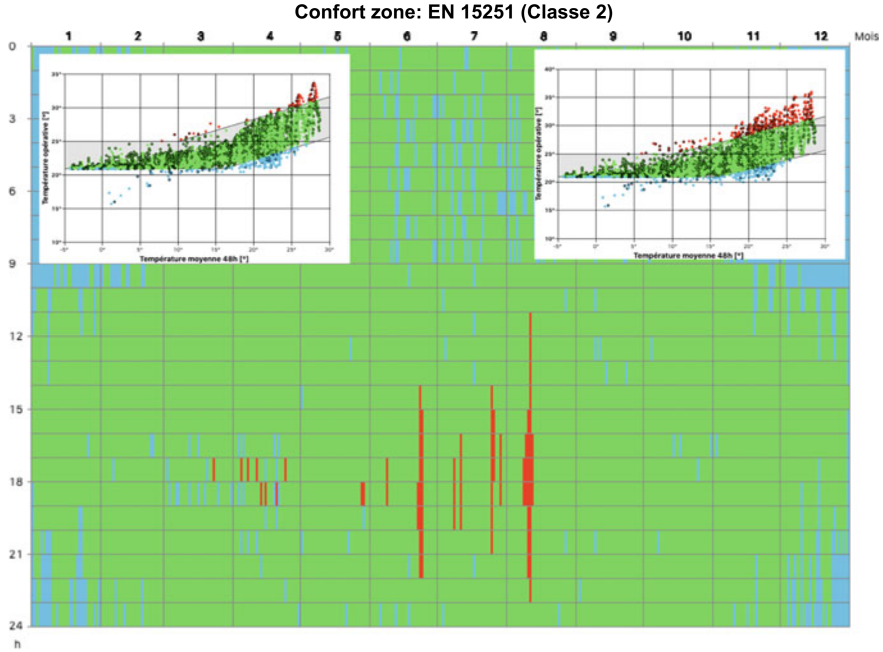


Fig. 12.27 Time chart for a room built in wood, located in Geneva, 84% glazed, with a screed on the floor, for a year with strong heat waves in June, July and August (as in 2003). On the top right is the EN 13251 comfort graph for perfect management of the blinds (43 h of overheating) and on the left, with a poor management with 151 h of overheating

comfort is impossible without night cooling or air conditioning. Another parameter that changed during the last 2 decades is the ventilation rates. Energy saving objectives and absence of smoking in the buildings divided the mechanical airflow by a factor of 2.

This section analyses the thermal behaviour of the reference office room under different climatic, microclimatic and design influences. Also in this section, the parametric analysis calculates the comfort and energy key performance indicators, but in this case considering climatic and microclimatic cases. Results show that with a ventilative cooling strategy, heat island effect in Geneva has little effect on indoor thermal comfort. Heat waves, becoming more intense and especially more frequent, have more significant negative impact. However, despite the negative impact of heat waves, comfort and energy indicators evaluated with dynamic simulation using DIAL + show that ventilative cooling still remains the answer to handle this new situation without increasing energy consumption of the building stock. Using the same method, simulation results using the predicted climate for 2060 show that ventilative cooling is able, in Switzerland, to mitigate the effect of climate changes. Buildings in these future-climatic conditions can still reach thermal comfort without air-conditioning, and this conclusion is valid for central European climate. Results show that a well-designed building, with adequate solar control, reasonable internal gains and appropriate day and night ventilation strategies, can support heat waves and climatic changes.

12.4.1 Climate Impact in Switzerland

In previous works in bibliography [16, 17], we find a characterization of the cooling potential of a climatic zone according to the weather conditions, without taking into account the needs of the building to be cooled. An innovation of Annex 62 is to evaluate this potential by considering the building as well. This consists of simulating a building according to the climatic conditions and evaluating the performance indicators. With the Annexe 62 introduction of energy performance indicators for ventilative cooling [4], in addition to the potential of a climate to provide comfort (calculation of hours in the comfort zone), we can assess the potential of a climate to reduce the cooling requirements for air-conditioned rooms. This can change current practices that tend to make air-conditioned buildings preferably closed without the possibility of opening the windows.

We evaluated the comfort indicators and the CRR for the office use for 6 typical Swiss cities. In order to characterise the climate of these cities with a single indicator, we calculated the number of hours when the outdoor temperature is above the comfort temperature according to ISO 7730 (mostly >26.5 °C). The number of discomfort hours of the outdoor air is low. This shows that the cooling potential of ventilation is high. It also indicates that the problems of summer thermal comfort for all Swiss climates are mainly a question of poor management of solar shading and poor design of ventilation openings rather that outside high temperatures (Table 12.15).

As we can see from the table, even well protected with good blinds, an office goes from one to two hundred hours of overheating to around several hundred, or even a thousand, in the main Swiss cities, except for mountain locations, where there are almost 400 h of overheating. This is confirmation of the first hypothesis at the beginning of this document, stating that modern buildings do not offer a dissipative element of summer heat. Simply opening the window during the hours of use reduces the hours of discomfort and the need for cold in a very significant way. Over-ventilation at night (Vm) alone does not provide sufficient reduction in cooling requirements and leaves hours of discomfort. Unfortunately, there is no software, as far as we know, that allows us to simulate a combination of window opening during the hours of use and over-ventilation at night by the ventilation system. Natural night-time ventilation, in all weather stations, offers sufficient comfort for the typical room being studied (Fig. 12.28).

Table 12.15 Comfort and energy indicators for office room and 4 ventilation strategies for 6 weather stations according to Meteonorm (typical year 1981–1991)

	Geneva	Payerne	Zurich	Sion	Lugano	La-Ch.-de-Fonds
Hours with Te > ISO 7730 (26.5 °C)	193	105	82	174	161	24
Summer days (Meteosuisse max ≥ 25 °C)	60	47	48	68	66	13
Tropical days (Meteosuisse max ≥ 30 °C)	15	8.1	9.1	16	8.1	0.3
Hours of overheating* V_0	902	880	779	983	1007	396
Overheating hours* V_d	40	4	11	30	30	0
Hours of overheating* V_n	0	0	0	0	0	0
Overheating hours* V_m $q_{SIA2024} \times 1$	177	50	68	104	305	0
DIAL + standard cooling requirements	9.9	7.4	6.4	9.8	12.4	1.9
CRR V_j	0.73	0.84	0.80	0.63	0.38	0.98
CRR V_d	0.92	0.95	0.94	0.89	0.80	1.00
CRR V_m $q_{SIA2024} \times 2$	0.78	0.85	0.81	0.81	0.66	0.95

*Overheating hours according to EN 13521 standard

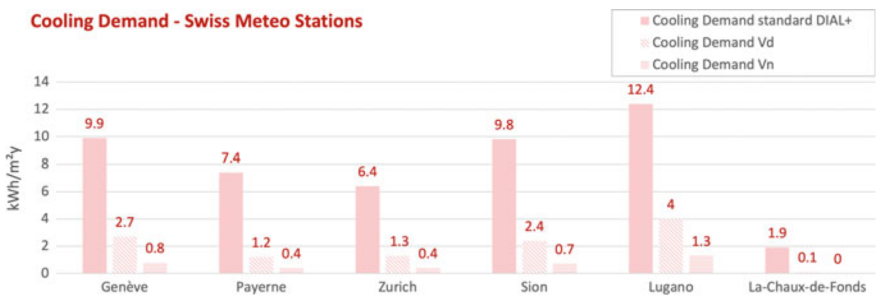


Fig. 12.28 Cooling requirements for 6 Swiss weather stations. Apart from the two extremes of the mountain climate, ventilation cooling strategies have a similarly high potential

12.4.2 *Effect of the Microclimate*

Over the past three to four decades, a number of studies on the microclimate of Swiss and European cities related to passive cooling have been carried out [18, 19]. The first studies are limited to the phenomenological analysis of the heat island, while the most advanced models focus on the calculation of surface and urban air temperatures at a given point in time, presenting the results in the form of a map with the spatial distribution of temperatures [20]. As computing power becomes available, dynamic models are beginning to emerge [21] with predictions of an acceptable degree of credibility. However, we are still a long way from being able to simulate local weather conditions and use them as input for dynamic building simulation software. The reference is still the weather at the reference site of a city. An interesting idea proposed by Tsoka [22, 23] consists in simulating a district with Envimed type software and producing average and extreme monthly temperatures for all the localities of a city using the reference meteorological file and validating them by real measurements on a few localities. Then, introducing these monthly results into the Meteonorm software it produces hourly files specific to a place in the city. But even if we put the energy and time into such an operation, the differences for the same building on the ground and third floors are just as significant as the difference between the reference and the specific site.

To quantify the effect of the heat island on ventilation strategies, we were able to find weather files with complete real measurements (temperature, radiation) at 3 sites in Geneva and we calculated the comfort and energy indicators by simulating the SIA 2024 reference office with DIAL + software as for the other influencing parameters. The urban climate data are for the year 2018. In addition to the "Genève Cointrin" station where Meteosuisse provides the measurements, we have the data for, Rue de la Prairie, at the canton's Engineering School, which is located in a dense urban environment, and for Batelle, at the university campus south of the city in Carouge, which is also on the outskirts at the other end of the city from the airport (Figs. 12.29, 12.30 and 12.31).

In spite of the indicative character of the temperatures of the private weather stations, shared on netatmo.com, and in spite of the errors inherent to these devices which can be badly placed in the sun or near a wall that stores heat, we can observe that in the central zone, and in the south-west of the city, in the Lancy–Bernex

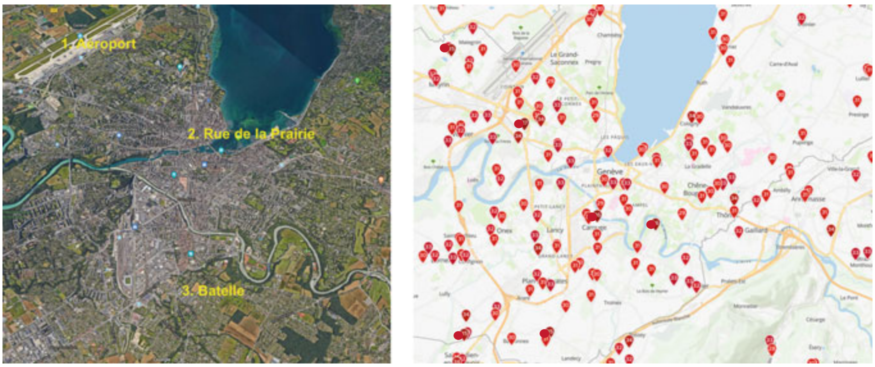


Fig. 12.29 Location of the meteorological sites studied in Geneva and outdoor temperature measurements at private homes by their private weather station shared on netatmo.com on a hot day

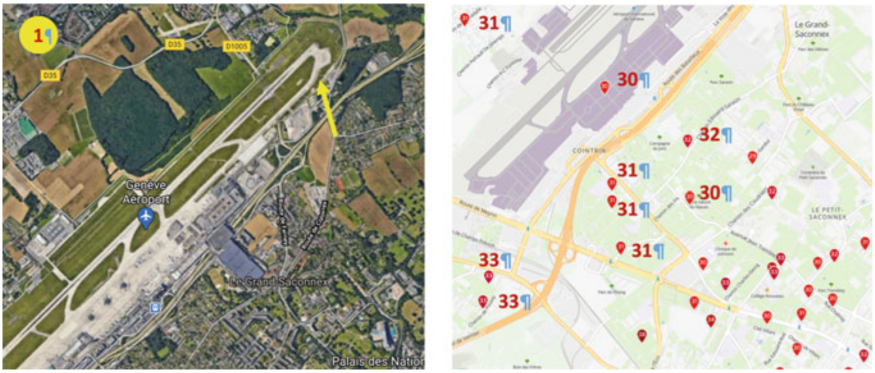


Fig. 12.30 Urban situation of the reference meteorological site and indicative values of the private stations connected in the vicinity

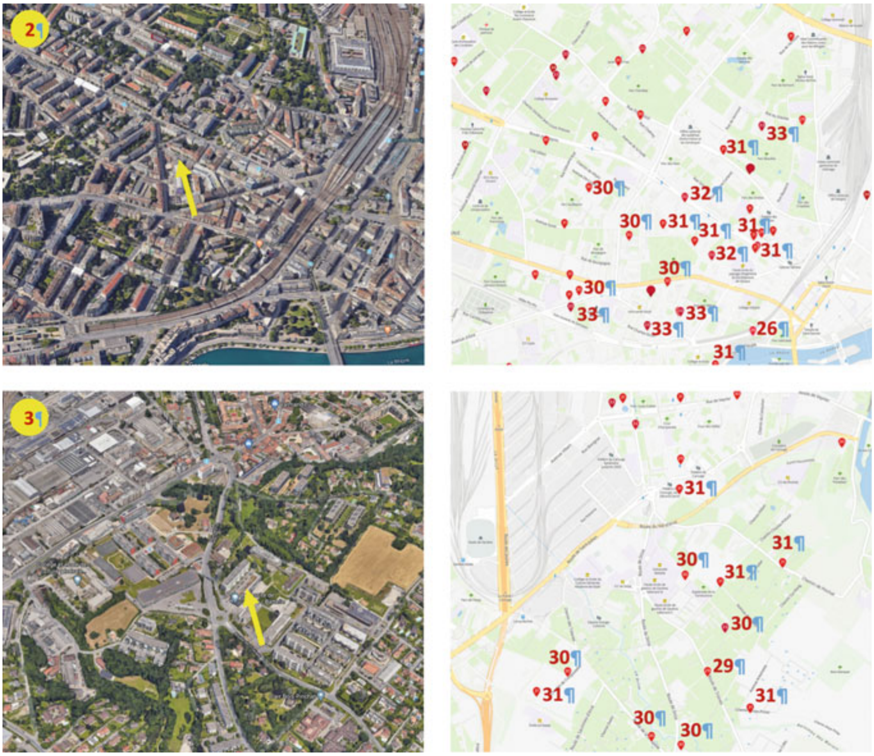


Fig. 12.31 Urban situation of the two analysed meteorological sites in the city and indicative values of the private stations connected in the vicinity

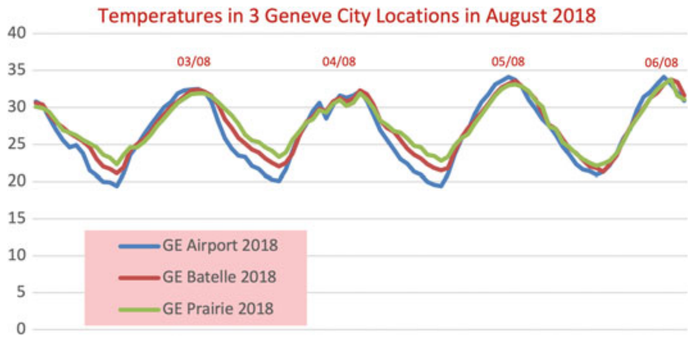


Fig. 12.32 Three weather stations in the city of Geneva to analyse the impact of the urban location on comfort and energy indicators

Confignon zone, the temperatures are higher (on the maps we have hidden some aberrant measurements where the sensor is obviously exposed to the sun). The very slight variation of the daytime temperature is in agreement with the real measurements. In reality we see in an obvious way only a variation for the night minimum temperatures and very slight variation for the day temperature (Fig. 12.32). On a hot day, we observe a minimum temperature of around 20 °C at the airport and 22–24 °C at Rue de la Prairie. The behaviour of the urban climate during a heatwave episode in 2018 shown in the Fig. 12.32 is similar to that simulated and observed in Basel by Wicki et al. [21], where we have higher air temperatures mainly at night. A very comprehensive study by meteosuisse on 5 Swiss cities shows the same phenomenon [24] for Lausanne, Zurich, Basel and Bern, where they could not measure an increase in daytime temperature or an increase in the number of tropical days, but an increase in hot nights with Tmin > 20 °C.

With all these real observations, we are far from the unfounded exaggerations about heat islands of the order of 5 or 7 °C in Geneva, far also from the perception that we should install air-conditioning all over Swiss cities because of urban heat islands. Furthermore, the idea that the airport is a rural area, or that the entire centre is a dense urban area, should be put into perspective, especially in a city on the lake with two rivers running through it. In Table 12.16 we observe an increase in the average temperature in general and in the average number of hot days ($T \geq 30$ °C) over the last 4 decades, but we do not observe an increase in daytime temperatures in summer in the city centre compared to the Cointrin airport. The year 2018, for which we have actual measurements for the 3 sites, is more similar to the maximum scenario of Météonorm, which takes for June and August the temperatures of the year of the great heat wave of 2003. However, this phenomenon, which is commonly called “heat waves” and which is becoming more and more frequent, will be analysed in the next chapter. As far as the “heat island” is concerned, the difference between Geneva Cointrin and the university meteorological sites of Rue de la Prairie and La Batelle is rather in the number of tropical nights (with $T \geq 20$ °C). We have 14 tropical nights at la Prairie instead of one at Geneva Cointrin and 7 at La Batelle.

Table 12.16 Temperature statistics for the reference weather station for 3 urban sites in Geneva

	Meteonorm			Measures		
	Cointrin Average 1981–91	Cointrin Average 91–2010	Cointrin summer max 91–2010	Cointrin 2018	Prairie 2018	Batelle 2018
Average annual temperature	9.9	11.0	12.1	12.3	13.0	12.9
Maximum temperature	30.9	33.6	35.0	34.1	33.8	33.8
Hours ≥26 °C	161	275	567	453	459	481
Summer days T_{max} ≥ 25 °C	35	51	78	82	73	77
Tropical days T_{max} ≥ 30 °C	3	6	21	28	21	24
Tropical Nights T_{min} ≥ 20 °C	2	4	15	1	14	7
Day T_{max} ≥ 30 °C and night T_{min} ≥ 20 °C	1	1	9	1	11	7

This makes the evaluation of the effectiveness of ventilation strategies more relevant, in order to quantify the real effect of these urban climate phenomena, as we rely on night-time coolness to combat daytime heat.

The Table 12.17 shows us that the reference office placed in the airport or in the city does not change significantly its thermal behaviour in summer, even if we have 14 tropical nights for the dense urban site in the city centre compared to 1 of the reference site. The heat demand increases by 2.5 kWh/m2 between the reference weather 1991–2010 and the weather of 2018 (a warmer than average year in summer with a significant heat wave). This is plus 25% in relative terms, but low in absolute terms. It should be noted that the reference cooling requirements according to SIA 2024 are 12 kWh/m^2. For the hot year 2018, the cooling requirements vary from 12.4 kWh/m^2 at Cointrin to 13.2 and 13.1 for urban sites. This is 6% more in relative value concerning the cooling requirements without night cooling. But the efficiency of night ventilation is sufficient to make air conditioning unnecessary for an office that can be naturally ventilated at night, regardless of its location in the city. For the daytime ventilation strategy and for mechanical night-time ventilation we see that the potential is even slightly better for Prairie and Batelle, but the situation remains almost the same (Fig. 12.33).

There could be particular situations in cities where there is significant local warming: the presence of a large tarred car park near a ground floor, the particular situation of an unvegetated, narrow and poorly ventilated urban canyon, etc., which could create unfavourable local conditions. These situations are not analysed, as they remain marginal, and they are more in the order of the study of the immediate

Table 12.17 Performance indicators for three meteorological stations in the canton of Geneva in 2018, compared with those of the "Cointrin 1991–2010" reference weather station

	Geneva Cointrin 1991–2010	Geneva Cointrin 2018	Geneva Prairie 2018	Geneva Batelle 2018
Hours with $T_e > 26$ °C	275	453	459	481
Hours of overheating* V_0	902	1014	1025	1026
Overheating hours* V_d	40	87	54	71
Hours of overheating* V_n	0	0	0	0
Overheating hours* V_m $q_{SIA2024} \times 1$	177	246	335	317
DIAL + standard cooling requirements	9.9	12.4	13.2	13.1
CRR V_d	0.73	0.57	0.61	0.60
CRR V_n	0.92	0.86	0.83	0.85
CRR V_m $q_{SIA2024} \times 2$	0.78	0.66	0.59	0.63

*Overheating hours according to EN 13521 standard

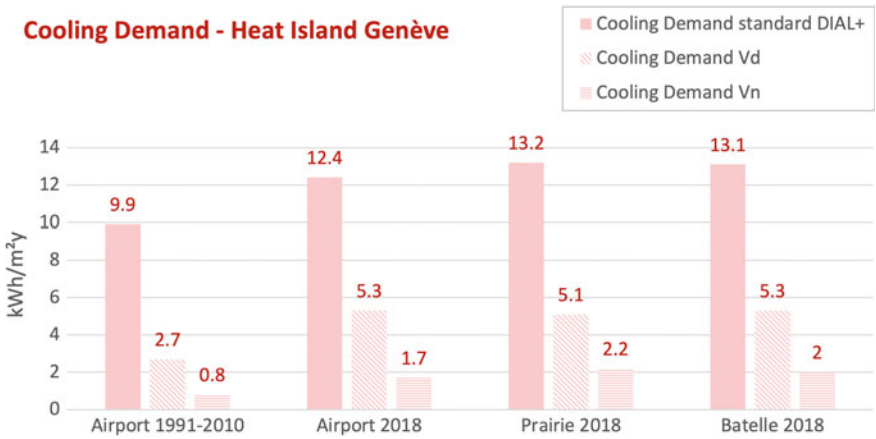


Fig. 12.33 Cooling requirements for the different cooling strategies as a function of the location of the reference office room in the city of Geneva. In all cases, night ventilation is sufficient as a cooling strategy

environment of the building rather than the heat island phenomenon which concerns the whole city. As we calculate the comfort indicators without taking into account the influence of the wind, any microclimatic phenomenon which creates a cool breeze (position in relation to the prevailing winds, position in relation to the lake or rivers) remain additional advantages compared to the analysed strategies which aim at cooling the substance of the building through the use of ventilation. The reference scenario corresponds to the situation where there is no wind, i.e. a possible canyon wind reducing effect is taken into account. Higher surface temperatures of the urban mineral, glazed and metal surfaces, affect seriously the radiative exterior temperature and thus the perceived temperature by people walking in the urban public space but they do not affect the air temperature and the interior climate of buildings. People who complaint for that, could use correctly their blinds or other solar protection and open their windows during night.

Influence of the urban situation
• Summer daytime temperatures, despite beliefs, are not higher in the city than at the airport in the Swiss and probably central Europe cities with similar degree of vegetation.
• Minimum night-time temperatures are 2–4 °C higher depending on the urban environment.
• The cooling requirement in the city do not present a significant variation depending on the urban situation.
• Day and night ventilation strategies are equally effective in the city centre or on the outskirts.
• Although the urban surface radiative temperature may affect seriously the perceived confront of pedestrians in the urban space, air temperature variation is slight and does not affect the interior comfort, especially using a night cooling ventilation strategy.
• For the Swiss (and central European climate) the observed significant rise of night air temperature in the urban sites does not affect seriously night ventilation cooling potential that remains an efficient cooling strategy.

12.4.3 Effect of Heat Waves

As we have already seen by analysing the behaviour of the reference room in 2018, the thermal behaviour can be significantly different from one year to the other. Climate change makes heat waves more and more frequent and more intense. The one in 2003 remained particularly striking because it was the first and the population and public health services of the countries concerned were not prepared to face it. The cities of Geneva, Lausanne and Basel recorded up to 7% increases in mortality during the months of June to August, during this great heat wave [25]. According to MeteoSwiss analyses [26], since the great heat wave of 2003, 5 years were registered with more than 20 tropical days and, among them, the last three are since 2017 and are consecutive. Heat waves are increasing in both number and intensity.

To analyse the effect of heat waves we simulate with DIAL + the comfort and energy indicators for the various ventilation strategies with 4 meteonorm weather

Table 12.18 Comfort and energy indicators for the standard office showing the effect of heat waves with 4 types of weather years from the past

	Cointrin 81–1990	Cointrin 91–2010	Cointrin max 91–2010	Cointrin 2018
Hours with $T_e > 26$ °C	161	275	567	453
Hours of overheating* V_0	863	902	1234	1014
Overheating hours* V_d	21	40	231	87
Hours of overheating* V_n	0	0	0	0
Hours of overheating* V_m $q_{SIA} \times 1$	146	177	550	246
DIAL + standard cooling requirements	8.6	9.9	17.8	12.4
CRR V_d	0.76	0.73	0.48	0.57
CRR V_n	0.91	0.92	0.78	0.86
CRR V_m $q_{SIA2024} \times 2$	0.74	0.78	0.57	0.66

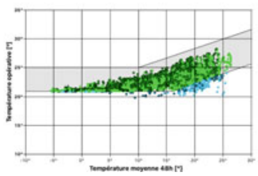
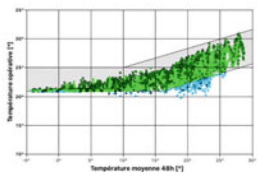
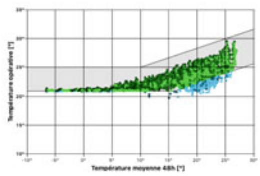
*Overheating hours according to EN 13521 standard

files: 1981–1991, 1991–2010, maximum values in summer (June 2003, July 1994, August 2003), and year 2018 (Table 12.18).

As can be seen from the previous table, heat waves significantly affect the summer behaviour of the building. With a summer like the one of 2003 in June–August, the cooling requirements rises from 9.9 kWh/m^2 with "normal weather for 1991–2010" to 17.8 kWh/m^2, an increase of more than 80%. This increase is 48% compared to the typical cooling requirements for a building according to SIA admitted "standard" conditions. In 2018, a summer that resembles to those of 2019 and 2020 in terms of tropical days (mean heat waves), heat requirements rise by 25% to 12.5 kWh/m^2. Daytime ventilation becomes clearly insufficient. An office without night ventilation, with windows only open during the hours of use (V_d) goes from 40 h of overheating (still bearable) to 231 with a heat wave like the one in 2003 and 87 h with those of 2018, 2019, 2020 (unbearable without ceiling fans). On the other hand, and this is positive, night ventilation remains a valid strategy even with the worst heat wave despite the increase in the average temperature of the room, and this is the main and more interesting conclusion of this analysis (Table 12.19).

If we zoom in on a period of great heatwave with tropical day and night, we can see that the maximum operating temperature is between 28 °C and 31 °C. Admittedly this is 2 to 7 °C lower than the outside temperature, but it is just at the limit of comfort. When interior temperature touches 31 °C, although exterior mean

Table 12.19 Comfort diagram EN 13251 with natural night-time ventilation for cooling for standard weather and two types of heat waves: a high (2003/1994) and a medium (2018)

Average 1991-2010	Max summer (2003/1994)	2018
		
Comfort largely assured	Comfort to the limit all summer long	Periods at the limit

temperature is ~ 25–26 °C with a maximum of 35 °C, many people would feel comfortable only with the use of a ceiling fan (Fig. 12.34).

Although a night-time ventilation strategy is capable of providing 100% comfort during the summer period during a heat wave for the room analysed, being at the limit of the comfort zone makes the indoor climate sensitive to the slightest error of use: few more internal gains, imperfect use of blinds, thermal mass covered by the furniture, additional radiation by a large screen facing the user... This may tilt the comfort out of the EN 13521 comfort zone. As these heat wave episodes become more frequent and intense with climate change, it is advisable to take passive or hybrid measures in addition to night ventilation (geothermal cooling from the ground, radiative cooling from lake water without cooling machines, ceiling fans, natural cross ventilation). It is also necessary to make the control of the ventilation strategy and the thermal gains more efficient (automation of blinds, automation of openings, electrical energy

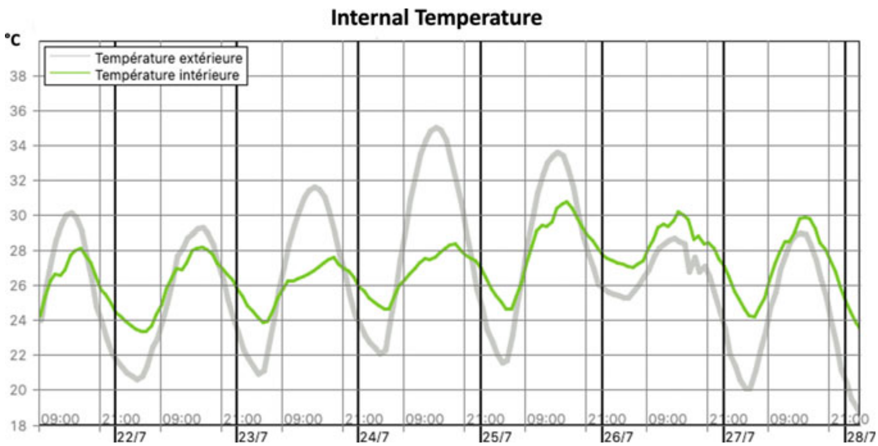


Fig. 12.34 Operating indoor temperature and outdoor temperature with DIAL + one week under a heat wave in July 1994

saving measures). A combination of other passive cooling techniques with ventilative cooling is rising resiliance of the building to extream climatic phenomena that may appear in the future.

Influence of heat waves
• Heat waves are becoming more frequent and intense with climate change that they announce.
• Comfort can always be ensured with the night ventilation cooling strategy even during the worst heat wave.
• Without an effective and well-controlled night ventilation strategy, comfort is not guaranteed despite the significant improvement indoor comfort with day ventilation. A combination of other passive cooling strategies, compatible with ventilative cooling are welcome to increase the feeling of freshness, especially ceiling fans or other soft radiative technics.
• The need for cooling is significantly increased during years with intensive heat waves. Cooling however does not means air conditioning. And although the increase in percentage is significant, the increase in absolute values is low for well designed buildings (less than 10 kWh/m^2).
• Ventilation strategies reduce cooling requirements by 48–86% even during the worst heat wave. Planners must consider them even in combination with air conditioning to reduce energy consumption (avoid it during mid-season for example).

12.4.4 Effect of the Environment Close to the Building

Although on a macro urban scale the climate is not altered in such a way as to significantly influence the behaviour of the building, the vicinity of the building may significantly affect it. Such obstacles may be:

– obstacles in front of or near windows (blinds, vent protections),
– solar absorption and the temperature of objects near the building (trees, other buildings),
– the temperature of the façade itself, creating a boundary layer around the building.

These elements can influence the effectiveness of a ventilation strategy. Either they can warm the air before entering through the window (e.g. blinds, protection of neighbouring building vents or dark coloured facades) or obstruct the airflow. They can do both (e.g. fabric blinds and double skin facades). Trees and neighbouring buildings may shade the window or cool the air.

Tsoka has shown that an urban canyon can raise the temperature locally, especially near the ground where heat is absorbed by the dark-coloured soil when the air stagnates [27] but it can also lower it if it is narrow and prevents the sun from warming the surfaces and keeping the night cool. It can also lower it if it has trees that act as sunscreen and evaporate moisture.

It would be illusory to imagine that, in addition to the effort of dynamic simulation of the indoor climate, building physicists would also simulate the outdoor microclimate. Results of the same study, considering four urban canyons in Thessaloniki

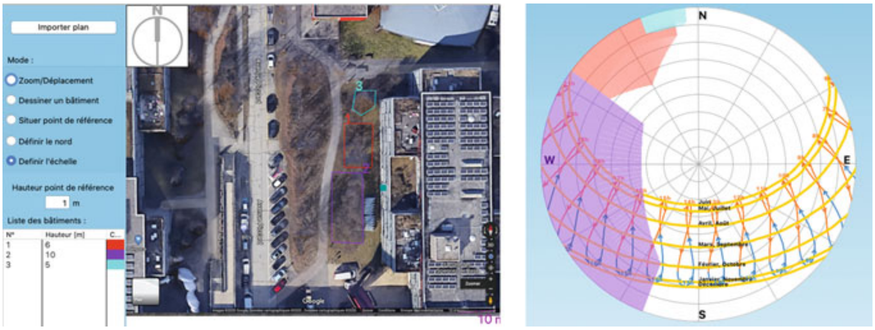


Fig. 12.35 Simulation of tree shadows in front of one of the EPFL buildings. The simulated office is on the ground floor in the middle of the building and the trees in ensemble 1 are 6 m high, those in ensemble 2 are 10 m high and those in ensemble 3 are also 6 m high. The trees are less than 5 m away from the window. The stereoscopic diagram shows that the West façade is sunny between 12 noon and 4 p.m. and shadowed after 4 pm

simulated with Evnimed [27], show that the maximum temperature increase due to the canyon effect is of the order of 1.5 °C on the ground floor and less for the upper floors. This is significant, but it does not concern the whole building. A solution to take into account a pejorative effect would be to use a warm year rather than an average year for the meteorological file. This would pejorate the result more than the warming of around 1–1.5 °C near the ground. On the other hand, we worsen the boundary conditions by excluding the effect of the wind, which compensates for some of the phenomenon. These modelling simplification tricks avoid all the modelling assumptions that can also lead to erroneous conclusions.

More than the outside temperature and the wind, the surrounding environment can modify solar radiation. In the DIAL + software it is easy to simulate near and far obstacles and their effect on the indoor climate, even from a google map image.

In the Fig. 12.35 we can see that the trees are well placed at a distance neither too close nor too far from the building of the Faculty of Basic Sciences at the EPFL (less than 5 m) from the west facing façade. This corresponds to what design guidelines consider optimum in most design textbooks. It can be seen that these deciduous trees do not provide shade between noon and 4 pm. If the building has no blinds on the ground floor and relies only on the shade provided by the trees, the cooling requirements increase from 9.9 kWh/m^2 to 13 kWh/m^2, i.e. we have an increase of 41%. Trees therefore in the case of offices do not provide a sufficient solution for every hour, even if they are placed at an optimal distance and at a favourable orientation (west). Planting the trees nearer to the façade would have counterproductive effects on natural lighting and thus to internal gains. We have simulated the cooling requirements with the protection provided by trees as additional sun protection in the presence of the movable blinds. These requirements are 9.7 kWh/m2 instead of 9.9, resulting in a CRR of 0.02. This is therefore negligible. The effect of these trees is therefore of only a sensitive nature. After 4 p.m. ground floor users can work with the blinds up or even if they are lowered, the solar radiation does not heat the blinds,

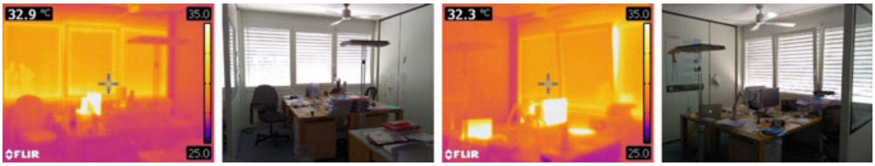


Fig. 12.36 Qualitative visualisation of air heating by an outside venetian blind. When we open the window for ventilation, the air is heated by the solar radiation absorbed by the blind. More the colour of the blind is dark higher the temperature rise it is

and therefore the air that passes through them. As a general rule, the temperature of the leaves of the trees follows the air temperature, which makes the ground floor office in a somewhat advantageous situation compared to another office that would be in front of a tarred car park, or another construction with a dark façade in the sun. It is practically impossible to do without solar protection thanks to trees. If we have good solar protection, trees offer secondary advantages (having a façade in the shade a few hours of the day without the need of using blinds).

The heating of blinds or facades by solar radiation is a real problem, especially for buildings that are naturally ventilated through windows. In the picture of Fig. 12.36 you can see that the blinds behind an open window are much warmer than the air temperature. Here the air temperature was around 28 °C, as was the inside temperature, while the temperature of the blind was over 35 °C. It is difficult to simulate the temperature of the incoming air, because it is a very dynamic environment, but various measurements have shown a temperature increase in the order of 1–3 °C, not counting the radiative effect of the warm surface of the exposed blinds. It is practically impossible to cool behind blinds in the sun, especially if they are not of white or very light colour. Even light grey blinds (the case of the photo) have an absorption coefficient of 0.4.

Blinds are not the only things that warm the air before entering the premises. Double skins or dark facades create a warm air canal or boundary layer, a kind of warm air curtain that goes upwards and envelops the building, preventing fresh air from entering through the windows (Fig. 12.37).

Fig. 12.37 Various situations that can create a boundary layer of warm air near the window. In the last case with fabric blinds, the sun protection not only has a warming effect, it also prevents air from circulating. This building had serious problems with summer overheating and the replacement of fabric blinds with slat blinds solved the problem, even though these blinds are less light-coloured than the existing ones

Many of the buildings in the pictures above had or have problems of summer overheating even though they comply with the conditions of Swiss standards for summer protection (g value of the solar protection <0.1, opening of the windows during summer, thermal mass). If these buildings are not air-conditioned, in other words if they have to rely on natural ventilation, sun protection devices prevent this in the presence of solar radiation. This is the only reason they do not offer thermal comfort.

On a southern facade this limitation of cooling potential lasts all day long, on an eastern facade the blinds limit morning ventilation until 11 o'clock, which is the time that is most beneficial to the cooling of the building or people. On a western facade they prevent ventilation in the afternoon, which is less problematic, as these are the hottest hours of the day when the windows are supposed to be closed in a comfortable room to limit ventilation with hoter air.

It is difficult to simulate these boundary conditions. The phenomena are complex, and the software does not provide automatisms to dynamically modify the g-value of a blind according to the ventilation or to modify the ventilation strategy according to the temperature of the blind. However, the modelling of these phenomena is necessary, because they are the main reason for the overheating of these buildings. In order to quantify the order of magnitude of the effect of the heating of the awning, we added 300 W of heat during the hours of sunshine on the west façade when the window is open on an average summer day when the outside temperature varies between 17 °C and 26 °C. We simulated the temperatures in a 60 cm wide double skin façade, open at the top and bottom across its entire width, with a blind of an absorption coefficient 0.4 (light grey) when the incident radiation is 300 W/m2. This fairly airy situation is not very far from a conventional blind without a screen in front. We have chosen equal inside and outside temperature to quantify pure heating and temperature rise. We can see in the picture that the heating of the awning is of the order of 9 °C up to 35.1 °C with these simulation conditions. The air temperature at the top of the canal rises by 2.4 °C (Fig. 12.38).

To quantify the effect of a grey awning in the west exposed facade, we used Leso-cool software from the solar energy laboratory (EPFL) adding 300 W of heat during the hours when the west façade is sunny and the window is open. This corresponds to a ventilation rate of approximately 300 m^3/h and with an increase in the temperature of the air entering through the window of approximately 3 °C (Fig. 12.39).

The air temperature in the room after 2 p.m. rises by about 0.5 °C on a normal summer day with an outside temperature of about 26 °C. The unpleasant effect of the awning being heated by the sun during ventilation is not only this increase in the average room temperature by 0.5 °C. There is also the effect of the incoming air which is warmer and accentuates the feeling of perceptive discomfort. In addition, a warming of the blind and the air around the window decreases the difference between the indoor and outdoor temperature, and even cancels it out, affecting the effective air flow through the window. The complexity of these phenomena exceeds the ability of professionals to integrate them into standard optimisation simulations. One simple way of taking this phenomenon into account would be to modify the g-value of the

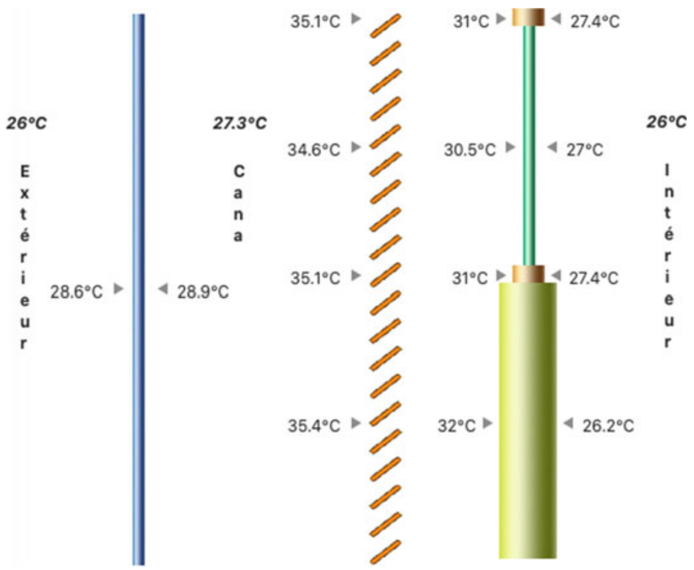


Fig. 12.38 Simulation of temperatures in a double skin façade on one floor with a bottom and top opening 60 cm wide and a blind with an absorption coefficient of 0.4 (light grey)

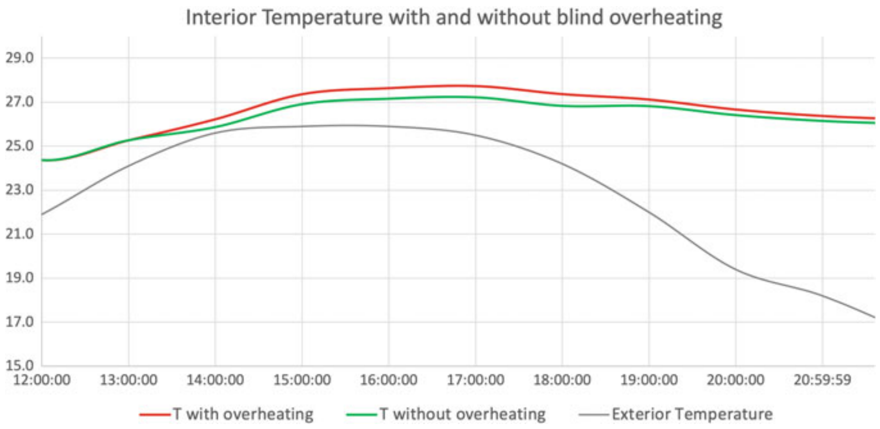


Fig. 12.39 Indoor temperature rise of the reference room (+0.5 °C) simulated with Lesocool with a temperature rise in front of the window of 3 °C, approx. 300 W for an air flow rate of approx. 300 m^3/h

glazing according to the colour of the blind during ventilation hours when the blind is under the sun.

Unfortunately, it is not possible to quantify all the comfort and energy indicators with the effect of overheating an awning. This requires major developments on simple software or a considerable modelling effort for more complex software. But if on an average summer day, we have ½ °C temperature difference over half a day, the comfort and energy indicators must be significantly deteriorated.

Influence of the environment near the window
• Urban canyons can increase the air temperature in the vicinity of the building.
• The changes concern the ground floor more than the upper floors.
• Canyons change temperature, but also solar radiation.
• A row of trees in front of a building has linited influence on the average behaviour of the building.
• Micro-urban changes have a low to medium influence on the entire building.
• The heating of blinds and façades can significantly modify the thermal behaviour of a naturally ventilated room (+0.5 °C on average during sunny hours).
• Warming of the air in front of and obstruction of the window is an important factor that can create overheating.

12.4.5 Effect of the Climate Change

Climate change is starting to be well documented, to the point where we can simulate building behaviour very easily. The latest report of the Federal Office of Meteorology and Climatology MeteoSwiss of 2018 describes the current situation, the expected changes and scenarios per region of Switzerland according to 3 scenarios for 2035, 2060 and 2085 [26]. During summer, the number of summer days as well as the number of tropical days and nights are going to change. Heat waves change in frequency and intensity. The great wave of 2003 with 50 tropical days in Geneva has not yet been repeated, but the years 2015, 2017, 2018, 2019, 2020 follow each other with 30 tropical days $\pm$ 5. The question is, what will the weather be like in the future. How it will be, for example, in 2060, when the buildings built or renovated today will not yet be renovated. According to the report by MeteoSwiss on Switzerland's main cities, especially on the Lake Geneva arc and in Ticino, we will go from 15 tropical days in the period 1991–2010 to 40 in 3035, to 60 in 2060 and to around 100 in 2080.

Meteonorm software offers the possibility to simulate the climate of the sites for which it has data, according to the IPCC assumptions on climate change as explained in the 2007 climate report [28]. We have simulated weather according to scenarios B1 and A2 for 2060. As the issue of heat waves is important in summer, we also simulated scenario A2 with summer maximum temperatures.

The pessimistic scenario A2 assumes an average temperature increase of 3.4 °C. As we have seen in the paragraph with heat waves, what is most problematic is not really the increase in the average temperature over the year, but the increase in heat waves. Meteonorm offers us the possibility to create an annual weather forecast according to the A2 scenario with summer maximum temperatures. This is the scenario we have called IPCC A2—Max (Table 12.20; Fig. 12.40).

The first observation on the table and figure is that climate change will cause an increase in cooling requirements. However, this increase is of the same order as an insufficient or poorly managed blind which is very common today. We go from 9.9 kWh/m^{2}a to 13.4 kWh/m^{2}a with the B1 scenario of a 1.8 °C increase and to 15.6

Table 12.20 Performance indicators with two climate change scenarios

	Geneva Cointrin	IPCC B1 Geneva Cointrin	IPCC A2—Geneva Cointrin	IPCC A2—Max Genève Cointrin
Hours with Te > ISO 7740 (26.5 °C)	193	307	375	813
Hours of overheating* V_0	902	1095	1182	1276
Overheating hours* V_d	40	109	171	418
Hours of overheating* V_n	0	0	0	29
Overheating hours* V_m $q_{SIA2024}$ × 1	177	405	472	696
Standard cooling requirements DIAL + kWh/m^{2}a	9.9	13.4	15.6	21.7
CRR V_d	0.73	0.55	0.52	0.36
CRR V_n	0.92	0.83	0.81	0.68
CRR V_m $q_{SIA2024}$ × 2	0.78	0.62	0.58	0.44

*Overheating hours according to EN 13521 standard

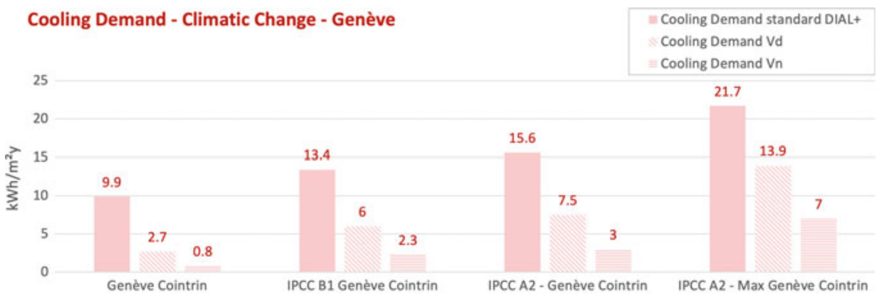


Fig. 12.40 Cooling requirements for 3 ventilation strategies and 2 scenarios

kWh/m^{2}a with the pessimistic A2 scenario of a 3.4 °C temperature increase. It is also observed that this temperature increase is perfectly manageable with an effective night ventilation strategy. On the other hand, the ventilation strategy only during the hours of use (V_d) becomes limited, with 109 and 191 discomfort hours. Comparing these results with the results of paragraph on heat waves, we can deduce that the buildings have already experienced climate change in June and August 2003 and in July 1994. The worst-case scenario of climate change (A2) will have a smaller average effect on buildings than in the summer of 2003. What will therefore change will be mostly the frequency of this phenomenon.

With the A2-max scenario we wanted to project ourselves into a heat wave in 2060 in addition to the worst-case scenario of an increase of 3.4 °C. In this case, which is likely to occur once in the next few decades, the cooling needs are 2.2 times more than today's average scenario, cooling only with daytime ventilation is clearly insufficient, and cooling by night-time ventilation becomes only just sufficient (29 h of overheating). The effect is important, but we may put it into perspective with the effect of an inefficient or badly used solar protection, or with a too much glazed building, which is of the same order. Concerning energy consumption increase for cooling requirements, someone must also put into perspective the reduction of heating requirements. The Table 12.21 shows that in average, the total energy requirements for cooling and heating are smaller in the Swiss climate with both optimistic and pessimistic climate change scenarios. With the extreme A2 scenario with a heat wave in addition, scenario that will happen exceptionally once a decade, there is a 5 kWh/m^2 increase in total heating and cooling requirements but in such a year there must be also more solar renewable energy production.

Table 12.21 Energy consumption indicators with two climate change scenarios

	Geneva Cointrin	IPCC B1 Geneva Cointrin	IPCC A2—Geneva Cointrin	IPCC A2—Max Genève Cointrin
Hours with Te > ISO 7740 (26.5 °C)	193	307	375	813
Standard cooling requirements DIAL + kWh/m^{2}a	9.9	13.4	15.6	21.7
Standard Heating requirements DIAL + kWh/m^{2}a	26.6	21.5	20.2	19.8
Total Heating and cooling requirements DIAL + kWh/m^{2}a	36.5	34.9	35.8	41.5
CRR V_d	0.73	0.55	0.52	0.36
CRR V_n	0.92	0.83	0.81	0.68

What we can retain is that despite the increase in the number of summer days, the increase in the number of tropical days or nights, cooling by ventilation remains an effective technique. The design rules do not change, and the night ventilation strategy will be able to offer acceptable comfort in summer for the typical studied room for the Swiss (and similar Central European) climate. Energy consumption for cooling and heating will not be affected, and lower heating requirements compensate higher cooling requirements. In addition to that, bad news for catastrophists, night cooling may neutralise cooling requirements and globally climate change can reduce building energy consumption for cold climates. However, even night cooling is not selected as a free cooling strategy, higher renewable energy production with sunnier days will contribute to additional non-renewable energy savings and global reduction of the building energy impact.

Taking too many precautions and starting to air-condition buildings "to be ready" for the climate change is not an adequate attitude, it simply contributes to justifying poor architectural design, polluting even more and accelerating climate change.

Heat waves are more difficult to manage, great heat waves will remain exceptional and time-limited events for Switzerland but designing buildings that are comfortable for an average summer also makes it easier to manage an exceptionally vigorous heat wave.

Influence of climate change
• In 2060, whatever the scenario for the progression of the phenomenon, there will be a significant increase in the number of tropical days and nights (from around 20 ± 5 tropical days today to 40 ± 10).
• In the worst-case scenario, an average year in 2060 will be somewhat less intense than the year already experienced in Switzerland in 2003.
• The impact of climate change on buildings in summer can be controlled using the same techniques we use today to manage the phenomenon of heat waves.
• Energy consumption of well-designed buildings will not increase due to climate change. Reduction of heating requirements will compensate increase of cooling requirements.
• For the Swiss climate (and equally Central European climate), ventilation cooling is still the most effective passive strategy and is sufficient to neutralise the impact of climate change in summer.

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Chapter 13
Historic Practices of Ventilative Cooling a Case Study on the House of Parliament, 1836–1966

Henrik Schoenefeldt

Abstract Ventilative cooling is a concern of contemporary practice, but research into the design of historic buildings has illustrate that the use of ventilation for cooling has been a much more longstanding practice. It was widely utilised in public buildings throughout nineteenth century and first half of the twentieth century, often in conjunction with other historic techniques. This chapter provides a critical examination of ventilative cooling as a historic practice, using the House of Lords as case study. This provides a setting where the challenges of cooling buildings before the introduction of mechanical refrigeration and air conditioning can be studied. Inside the two debating chambers ventilation was utilised for cooling purpose in three different ways. In addition to (1) reducing the indoor air temperature, ventilation was utilized to (2) harness the cooling effect of air movement, (3) and also to cool the architectural fabric, following the principal of night-purge ventilation. Focusing on the period from 1835 until 1950 and taking a realist perspective this chapter re-examines the experience and knowledge that users, scientific researchers and technical staff had acquired, illuminating the practical challenges of achieving thermal comfort through ventilative cooling, covering both mechanical and natural methods. This shows that historic practices not only engaged with the technological but also managerial and user-experience perspectives.

Harnessing the Instrumental Value of Historic Research for Sustainable Design:
In every history period, including ours, the design of building services is shaped contemporary understanding of technology and building science. This applies also to the use of ventilative cooling principles in architecture, which, as this chapter will show, has been widely deployed in the 19th century and early 20th century in Europe and the US. In the context of historic building conservation, which is confronted with the challenge of balancing heritage and environmental requirements, it important for designer to actively engage with the differences between our current understanding and that of the past. Much of this past knowledge has been lost, yet historic research

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enables us to uncover this past knowledge. Through a detailed case study of the historic use of ventilation cooling in the British House of Lords over the period from 1835 to 1950, this chapter illustrates that historic research cannot only offer insight into the original design but also the actual performance of past approaches to ventilative cooling. That latter included the practical challenges encountered in its day-to-day operation. By offering empirical evidence of the potential and limitation of these historic methods, the latter provides an in-depth and critical understanding of these historic methods. This critical understanding is necessary to address three fundamental questions:

- Is it viable to revive past approaches to ventilation cooling principles in historic buildings?
- Could the revitalisation of historic principles provide an alternative approach to the installation of modern mechanical systems?
- Could it help to reconcile the heritage and sustainability requirements in architectural conservation?

13.1 Introduction: Taking a Historical Perspective

The preceding chapters have examined ventilative cooling as a concern of contemporary practice, but historic buildings illustrate that the use of ventilation for cooling has been a much more longstanding practice. It was widely utilised in public buildings throughout 19th century and first half of the 20th century, often in combination with other historic cooling techniques.

Amongst Victorian buildings designed to utilised ventilative cooling, was, the Royal Albert Hall [1], National Gallery [2] and British Museum but also various market halls and exhibition halls, such as Smithfield market and the Crystal Palace of 1851 [3, 4]. Also icons of the modern movement, such as Ludwig Mies van der Rohe's Crown Hall in Chicago, were designed utilise ventilative cooling to mitigate overheating issues. Today the interest in the use of ventilative cooling is driven by a search for more energy efficient cooling techniques, but in the 19th century its use was a necessity, driven by the technical limitations of historic refrigeration methods. As such historic buildings provide setting/where the challenges of cooling buildings before the introduction of mechanical refrigeration and air conditioning can be studied.

The objective of this chapter is to explore ventilative cooling as a historic practice, using the Houses of Parliament as case study. The debating chamber, subject to significant overheating issues, provide intimate insights into the historic practices, illuminating how ventilative cooling techniques were deployed to mitigate overheating encountered during hot weather and under crowded conditions. Inside the two debating chambers ventilation was utilised for cooling purpose in three different ways. In addition to (1) reducing the indoor air temperature, ventilation was utilized to (2) harness the cooling effect of air movement, (3) and also to cool the architectural fabric, following the principal of night-purge ventilation.

This chapter focuses primarily on the experience within the House of Lords, but excursions will be undertaken into some parallel investigations inside the House of Commons. The latter was built in 1852 but was destroyed during air raids in 1941 and subsequent rebuilt incorporating modern air conditioning and mechanical ventilation technology. In the House of Lords, historic practices of ventilative cooling continued to be deployed for another 16 years. Air conditioning was not introduced in this upper chamber before 1966. Covering the period from 1835 until 1950 this chapter re-examines the experience and knowledge that users, scientific researchers and technical staff had acquired, illuminating the practical challenges of achieving thermal comfort through ventilative cooling, covering both mechanical and natural methods. These not only engaged with the technological but also managerial and user-experience perspectives. To recover these historical experiences with the use of ventilative cooling, it was necessary not only to study its physical architecture, but also its operational history, an area that overlaps with the domain of facilities management. Archival material, such as log-books, letters, scientific reports and parliamentary papers, was used to uncover some of the tentative knowledge acquired through day-to-day observations and user feedback, but also the deeper understanding gained through formal scientific investigations.[1] These records offer critical insights into the ways the climate and ventilation managed, using a combination of mechanical and passive strategies, how it had performed and also how it was experienced by users. Several attempts were also made to improve the cooling arrangement, which involved physical and operational changes but also hypothetical design studies, exploring the possibility of more fundamental changes to the historic practices.

13.2 Preliminary Investigations

Ventilative cooling at the brief and design stage, 1836–1851

The principles underlying the ventilation system of the House of Lords was the outcome of extensive investigations into the fundamental issues of ventilation and thermal comfort inside legislative chambers, which were untaken after a fire in 1834 had destroyed the original Houses of Parliament. Overheating heating problems had been common inside the original debating chambers, and the decision to create a new purpose-built parliament, offered the opportunity to re-visit these issues in the light of new technologies and scientific research. These inquiries began with the appointment of a Select Committee in 1835, which the House of Commons had charged with the task of consulting experts and reviewing hypothetical proposals for modern ventilation systems. Amongst these was a proposal by the Scottish physician David Boswell Reid, which was significant due to its focus on the physiological aspects of environmental control, highlighting thermal comfort as an important aspect

[1]The research is based on archival material held at the National Archives in Kew, Parliamentary Archives and Strategic Estates Archives in Westminster and at Historic England's architectural archive in Swindon.

of ventilation in legislative chambers. This focus was reflection of Reid's background in the medical sciences and chemistry. Although Reid did not have a background in architecture or engineering, he had undertaken research into indoor air quality and the thermal comfort, which included experiments on the thermal perception of internal currents, which too account several parameters, such as velocity, direction, distribution and temperature and humidity. Inside a series life-size models, Reid also trialed methods of diffusing the air currents inside hermetically sealed spaces, through the use of perforated floors, ceilings and walls.

Finally, a large space is devoted to.

In Westminster Reid proposed hold parliamentary sittings within the artificial atmosphere of a hermetically sealed chamber. This chamber was to be supplied with conditioned air through a central ventilation network, containing facilities for cooling, heating and filtration. The air entered through perforated floors and was extracted at the ceiling (Fig. 13.1). The ventilation was driven entirely by the natural convection of hot air ascending a tall shaft. Reid claimed that convection, enhanced artificially with the aid of furnaces, will provide the higher flow rates required to '*ventilate an overcrowed or heated room*' [5]. The system had to mitigate the impact of heat derived from external sources, such as sunlight and high outdoor temperatures,

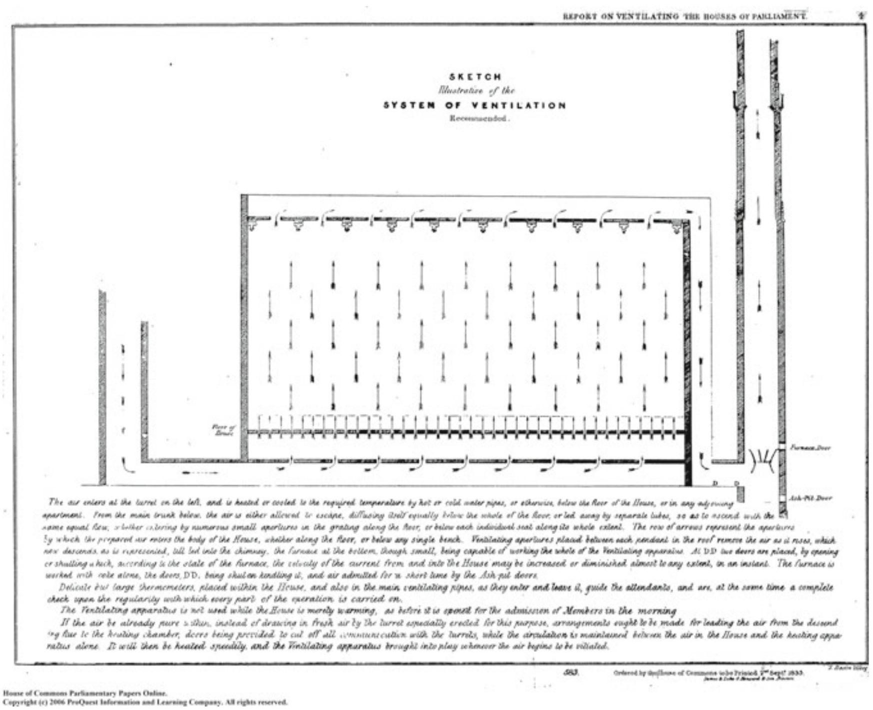

Fig. 13.1 Cross-section showing principle of Reid's scheme (1835 (583) Report from Select Committee on the Ventilation of the Houses of Parliament, plate 13.4)

as well as internal heat sources, such as gaslights and large numbers of people. The latter was significant as it could reach numbers of 400 in House of Lords and 800 in the House of Commons, during major debates. Reid was aware that his concept would only succeed if the cooling effect produced by the currents of the incoming air can be kept within a comfortable range, taking into account velocity and temperature as interpendent variables. If both are well-managed he believed that it would be '*utterly impossible for it to abstract such quantities of heat from the human body as to make any one feel any inconvenience from it*' [6]. For this purpose he proposed to physically cool and heat the supply air, using hot and cold water pipes, but also to reduce the intensity of the incoming air. His proposal was to cover the entire floor with 10.000 small inlets, arguing that it would allow to prevent excessive currents even if at times when the ventilation had to be boosted. Although Reid's statement focused on the avoidance of excessive air speeds as a source of discomfort, engaged critically with air movement as an aspect of thermal comfort.

The Select Committee did not recommend the adoption of any specific schemes or technologies, but over the following four years Reid to test and refine idea experimentally, in which questions of thermal comfort remained the focus. These explorations began with trials inside a large physical model, erected at his private laboratory in Edinburgh, and in autumn 1836 he was also commissioned to remodel the ventilation of the Temporary House of Commons based on his principles. This was built as provisional debating chamber in 1835 to accommodate sittings until the completion of the parliament building. It was occupied for 15 years and allowed Reid to tested and develop his principles of ventilation under real-life conditions, involving MPs directly in the process of evaluation and improving the thermal environment from a user-experience perspective—the application of these principles in Charles Barry's House of Commons is examined by Schoenefeldt [7]. Reid discussed his inquiries in his book *Illustrations of the theory and practice of ventilation*, published in 1844. This includes a whole section examining physical factors affecting thermal comfort, including air movement [8] and it also describes how this knowledge was utilised in the day-to-day operation of the Temporary House.

Similar to his earlier proposal the temporary chamber was sealed and supplied with fresh air through a perforated floor (Fig. 13.2 and 13.3). The air movement was sustained by a large chimney with a coke fire. It was equipped with warm air central heating, which contained arrangements for humidification, air filtrations and cooling. The air was cooled by evaporation, utilising water sprinklers, and by circulating cool water through radiator cases. Attempts were also made to cool the air with natural ice, but these did not go beyond the stage of short trials These methods were complemented by ventilative cooling. Reid reported that the ventilation had to be use to increase comfort in summer and to '*moderate the heat produced by so many on a limited space*' [8: p. 179]. During ordinary weather and levels of occupancy Reid recommend a supply of 10 cubic feet per minute per person, but in hot weather it was raised to between 40 to 60 cubic feet per minute for cooling. He noted that such levels were necessary if comfortable temperatures were to be maintained without resorting to artificial cooling. Ventilation was the principal cooling method, and Reid exploited three different approaches to improving comfort through ventilation. In addition to

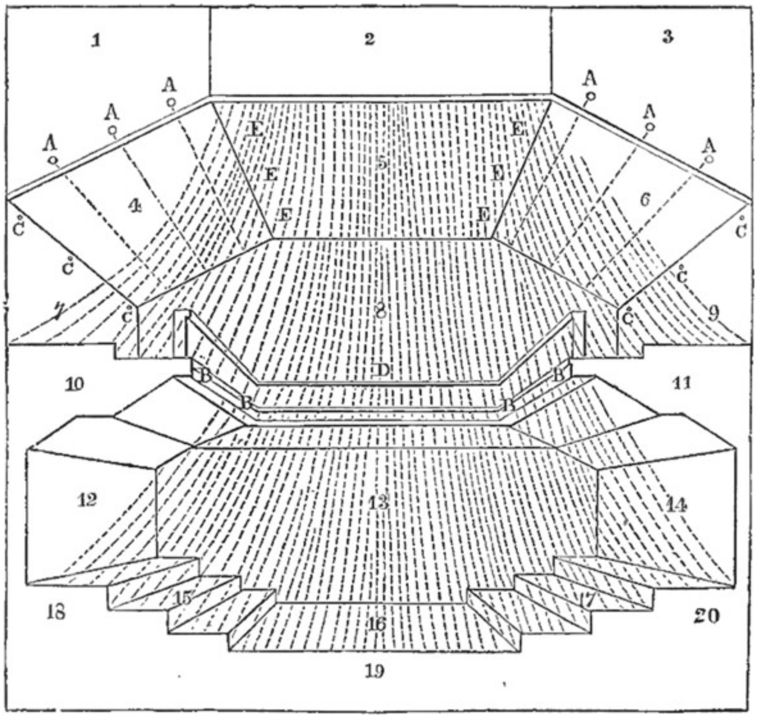

Fig. 13.2 Diagrammatic cross-section showing diffusion of air (Reid, Illustrations, 1844, p. 300)

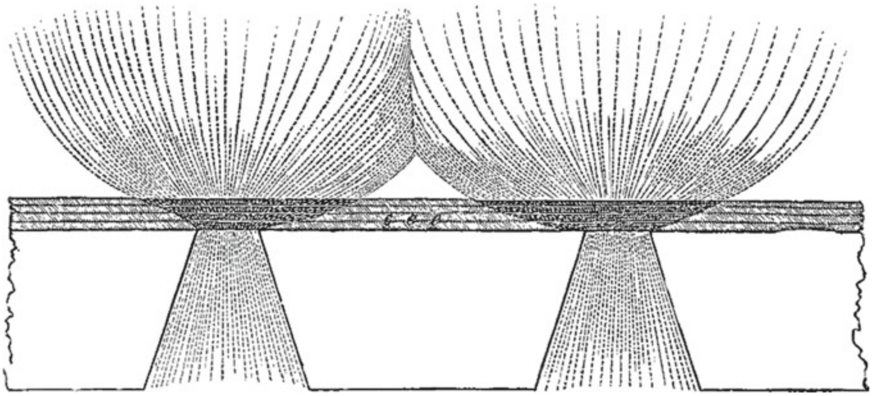

Fig. 13.3 Detail of floor inlets, showing diffusion of air by perforated floor and carpet [8: p. 282]

night purge cooling, ventilation rates were increased for the purpose of lowering the air temperature and also for harnessing the cooling sensation of currents. The latter was particular critical as high air temperatures could not always be prevented. Reid wrote that '*an atmosphere sultry and oppressive from its high temperature, might be rendered cool and pleasant to the feelings by increasing its velocity, provided the temperature is actually below that of the human frame*' [8: p. 185]. He claimed that increased air movement, even at a temperature of 75 °F (23.89 °C), 'may be rendered cool and pleasant to the feelings' [8: p. 295]. To successful implement his strategy Reid also had to introduce formal procedures for environmental control and monitoring, which, aside from the systematic recording of temperatures and technical operations incorporated a process for collecting and processing user feedback. This was critical as many physical factors affecting the perception of warmth, including air movement, were not routinely measured (Fig. 13.4). This feedback highlighted some of practical difficulties with implementing his cooling strategy from a user-perspective [9]. MPs reported that the current produced a chill around their feet and legs, in particular during crowded debates or hot weather when the ventilation rate was increased to reduce the air temperature.

This issue was revisited in 1840s when Reid became formally employed by the government as a consultant to work with the architect Charles Barry in the development of the ventilation and central heating for the Houses of Parliament. In the context of the House of Lords Reid explored an alternative approach to supplying air. This resulted in changes to the architecture of the floor. In his scheme, which had been developed between 1842 and 1846, Reid proposed to confine the floor inlets to positions where the feet and legs of the Lords were not exposed to direct currents. This

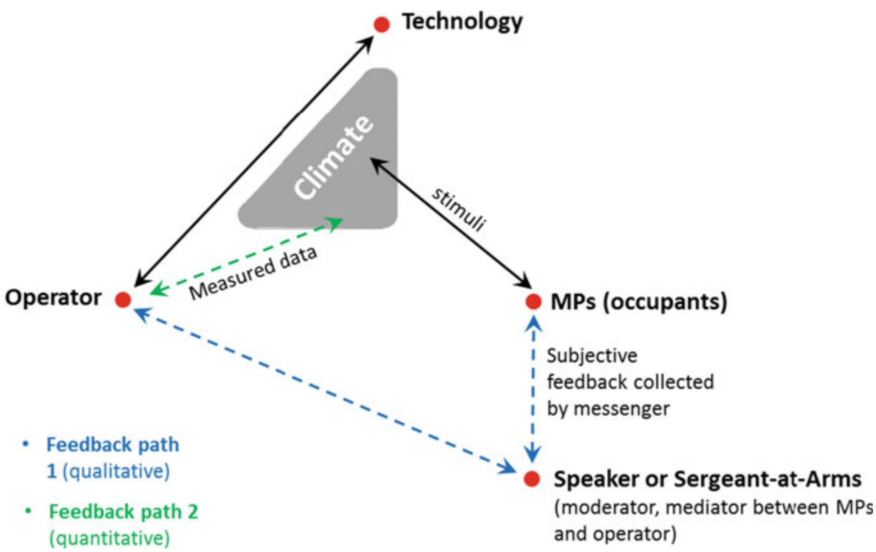

Fig. 13.4 Diagram of feedback mechanism (Author's own diagram)

required Reid to carefully plan the positioning of inlets, using any available surfaces, such as skirting boards, wall panels or tables [10]. The air, he argued, was to '*flow in and rise as gently as the movement of the air on a mild summer's evening*' [11]. During ordinary debates the air was supplied through inlets furthest away from the benches to protect Peers from direct currents. A second system of inlets was provide within the benches and inside the gangways [12]. As the air entered through the back of the benches near the feet, the use of these supplies were to be restricted to periods when the main inlets were not sufficient or if requested specifically by Members. On 14 August 1846 Reid said that only intended to activate these inlets only during 'hot and sultry' weather, over periods when the chamber was exceptionally crowded [13].

> On extreme nights when Members of the House of Peers might complain of the state of the atmosphere, and wish a still greater portion than could be supplied by those means, then I would propose to bring in the back of the seats and using the steps as surfaces of diffuse ventilation under such control as the Peers themselves might desire' [14]

The design for this highly complex scheme was never fully resolved. Largely due to delays caused by difficulties with completing his scheme, the House of Lords in 1846 voted to terminate Reid's involvement in the design. The responsibility for completing the system was transferred to the architect. He altered parts of Reid's plans to realise a different approach to achieving comfort, focusing on the interrelationship between air movement, radiant heat and air temperature. In his new scheme the perforated floors were sealed and the inlets for the primary air supply moved into the ceiling. Air was supplied and extracted almost entirely through the ceiling. Supplementary outlets were provided at mid-level, using opening in the coving under the side galleries, and only a small quantity of the air was admitted through outlets at floor level as part of a back-up system [15] (Fig. 13.5). Barry argued that the introducing the air from above would overcome the problems with currents entering close to the body [16], noting that it was '*impossible to avoid the inconvenience of partial currents when air is admitted from the floor, or near the person*' [17] This had the advantage of allowing cooler and larger quantities of air to be injected at a greater distance from the benches. The temperature of the supply air itself was kept low, and the effect of the cooler air was compensated through the provision of radiant warmth, using underfloor heating. The air introduced through the ceiling was only kept at around 62 °F (16 °C), whilst the surface temperature of the floor was raised to 67 °F(19 °C) [18] (Fig. 13.6).

13.3 Performance Issues

The examination and remodeling of the House of Lords, 1847–55

Barry's system was in use from 1847 until 1854 and over this period its performance became subject of two formal inquiries, in which the use of ventilative cooling and its implications for thermal comfort was a major focus. These inquiries, coordinated by

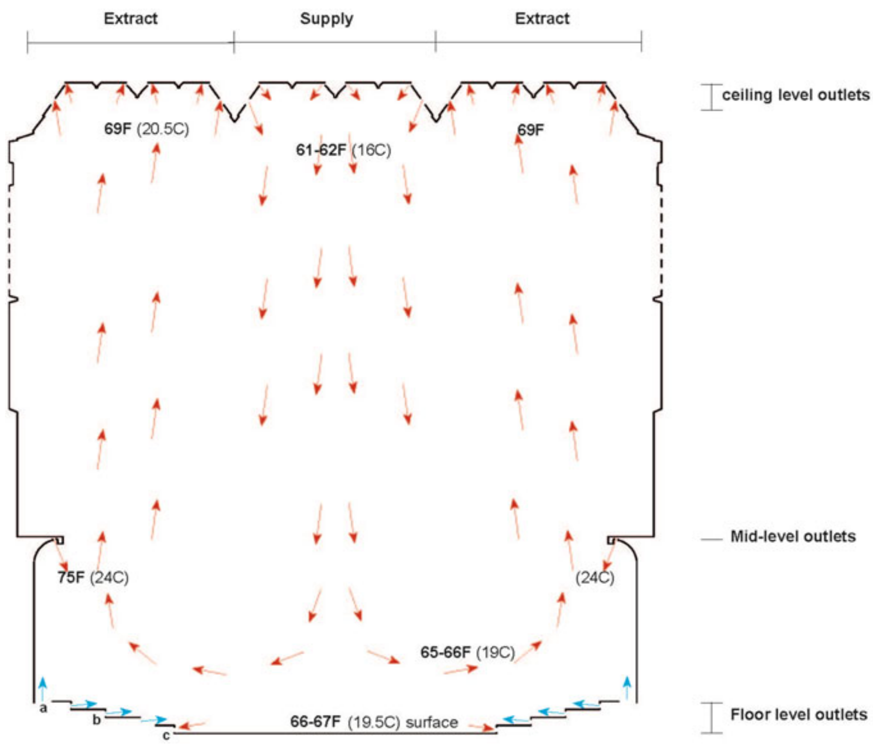

Fig. 13.5 Diagrammatic cross-section, showing arrangements of outlets in Barry's scheme. (Author's own drawing) Key: outlets in floor: **a** perforated grating on top tier of raked floor, **b** fresh air outlet in risers of raked seats (2nd to 4th tier), **c** vitiated air outlets in riser behind front benches

Select Committees in 1852 and 1854, were undertaken as many Lords were dissatisfied with the thermal conditions. The Office of Works, a government department responsible for managing the operation and maintenance of the Houses of Parliament, also made several technical alterations in an attempt to improve comfort.

Transcripts of interviews with individual Lords, conducted in March 1852, provide some insights into their experience of the conditions. Although the personal experiences were varied, they highlighted draughts and overheating as the main cause of discomfort. The latter was the result of overcrowding and large heat gains from gaslights and sunlight. Lord De Ros reported that many Peers perceived the atmosphere as dead and artificial, which he attributed to the uniform temperature and the absence any sensible air movement [19]. In contrast, Earl Lonsdale perceived the thermal environment as highly changeable' noting that it was 'sometimes very hot, other times very cold, with cold draughts'. During the sitting on the 29 March 1852, he reported that the temperature had reached 70F, leading to complaints from several Peers and the clerk at the table was sent to the engineer to make a request for adjustments. The temperature was reduced to 66F, but according to Lonsdale it was

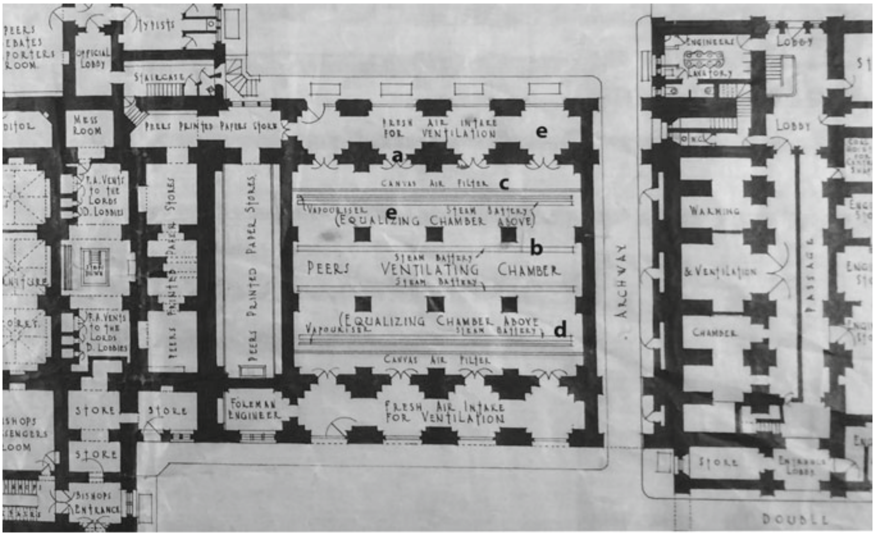

Fig. 13.6 Plan of ground floor, November 1937, showing original arrangement inside lower plenum level, including **a** louvred inlets facing the courtyard, **b** steam batteries, **c** canvas air filter, **d** vaporiser for humidification, **e** water jets in front of intakes. (Plan of Ground floor, November 1937, Office of Works (Strategic Estates Archive, nr. 000381/s)

still 'too hot and oppressive' and argued that there was still a 'deadness and fustiness in the air.' [20]. Lord Redesdale noted that the system struggled under crowded conditions. Lord Lansdowne and Early Grey mentioned occasional problems with cold drafts around the legs. Grey reported that the chamber '*was at one time very hot, and then came a current of very cold air to one's feet.*' [21] and also noted that the sunlight entering the large windows caused overheating during the summer months.

In 1852 several alterations were undertaken, which focused on improving the conditions around the benches on the main floor through increased ventilation. These was achieved by introducing a stronger fan for the air supply, increasing the height the ventilation shaft, and by providing new outlets at floor level, which allow hot air to be extracted downwards. These early interventions, however did not succeed in improving comfort, and in 1854 the House of Lords appointed another Select Committee to re-examine this issues. Collaborating with the Office of Work and the superintendent of the ventilation the Committee evaluated the performance of the existing arrangements, conducted technical trials, and engaged Goldsworthy Gurney, a physician with an interest in ventilation, to develop plans for improving the internal conditions. The focus of this inquiry was on overheating and air movement as the main source of thermal discomfort. This inquiries showed that, despite the introduction of a stronger fan, the ventilation was unable to counteract the large heat gains from the gaslights. The attendants generally kept an atmospheric temperature of 65 °F–66 °F (18.33 °C–18.89 °C), but when the gas lights were turned on it rose 7 °F (3.89 °C) within one hour. The lights emitted a large quantities of heat, which caused the indoor temperature to rise and also exposed the Lords sitting inside the galleries to a strong radiant heat. Measurements, taken when the House was unoccupied, showed that the gaslights were capable for raising the temperature from 62 °F (16.67 °C) to 68 °F (20 °C) [22]. In addition the fan increased the intensity of the fresh air currents and these created turbulences around the Lords feet and legs. In March 1854 Alfred Meeson, superintending engineer in charge of the ventilation, conducted a smoke test to study these currents [23]. These showed that the fresh ascending from the centre of the ceiling formed column of cool air whilst the warm air ascended on the sides to the side panels. When hitting the floor, however, the downward currents moved sideways sweeping across the benches, chilling the Lords' feet and legs [24].

Gurney's proposal, designed to overcome these issues, was adopted in 1854, following a successful trail inside the House of Commons. In the House of Lords Gurney reinstated the use of perforated floors for the air supply. Arguing that it would allow the incoming air to be diffused more effectively, uncovered the cast-iron floor plates and added a layer of '*cord sisal matting*', a coarsely woven fabric that was permeable to air [25, 26]. In a report to committee, dated 10 April 1854, he wrote the Barry's approach was producing a turbulent atmosphere and that his objective was to bring it into a 'quiescent state' [27]. Making reference to his trial in the House of Commons, he argued that the use of perforated floors allowed introducing 7,000 cubic feet of air per minute without producing any 'sensible motion' around the body [28]. The air movement was closely regulated through a system of manual controls, operated by a team of attendants under Gurney's supervision. These constituted an array of shutters and louvres inside the air chambers. One set of controls were provided to control the air supply and two sets to control the quantity of hot air going into each ventilation shaft. Their position of these control is shown in Figs. 13.7 and 13.8. The air was also 'conditioned' in air chambers below the floor [29], the plant is shown in Refs. [30, 31]. The fresh air was introduced through eight large intakes facing the courtyards on the east (Peers Court) and west side (State Officer's Court) of the House. These constituted of large doors with louvers, which were manually adjusted to regulate the air supply. The lower air chamber contained canvas screen (air filtration), steam batteries (heating), and vaporisers (humidification)—a description of Gurney's can be found in John Billings [32, 33]. An evaporative cooling system, constituting an array of 'Fine water jets,' was stationed outside the air intakes [34] (Fig. 13.6). The ceiling of this lower chamber had twelve rectangular valves, by which the 'conditioned' air was directed into an upper air chamber, which was referred as the 'equalising chamber.' Its purpose was ensure that the air entered at uniform temperature and velocity across the floor.

The internal climate conditions and their effect on user experience, were closely monitored as part of the routine management procedures. The temperature was monitored, using thermometer in different locations, hourly readings were recorded inside log-books [35]. One of the original log books has survived (Fig. 13.9). It covers the period from 1943 to 1948, during which the Lords chamber was occupied by the House of Commons [36]. Other data was reproduced in letters and parliamentary reports. Air movement, however, was not measured as part of the routine monitoring

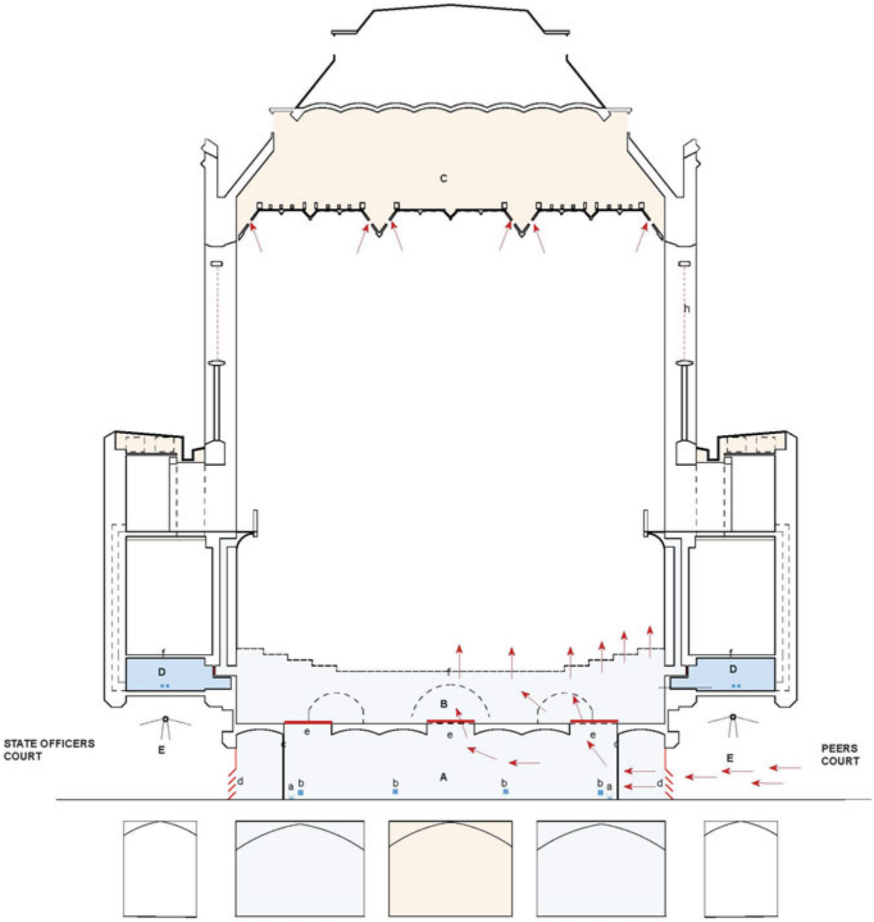

Fig. 13.7 Cross-section showing ventilation arrangements after 1854. (Schoenefeldt) Key: **A** Lower air chamber; **B** Equalising chamber below floor (containing additional steam batteries at south end); **C** Vitiated air chamber above timber ceiling; **D** Fresh air chamber under Division Lobby, containing steam pipes; **E** Cloistered passages in front of the air intakes; **a** humidification channels; **b** steam batteries (heating), **c** Canvas screens (filter); **d** louvres of air inlets inside vaulted passages; **e** valves between heating chamber and 'equalising chamber; **f** perforated cast-iron floor; **g** fine water jets (evaporative cooling); **h** openable window sections

procedures, and, as the perception of thermal environment was also highly subjective, it was evaluated based on direct observations and user feedback. As a result the system became dependent on regular interaction with users. For this purpose the operational procedures incorporated the principles user engagement that Reid had developed and trialed inside the Temporary Houses of Commons [9]—the role of user engagement in the day-to-day management of the climate and ventilation in the House of Commons chamber have been examined in detail in two articles [37, 38].

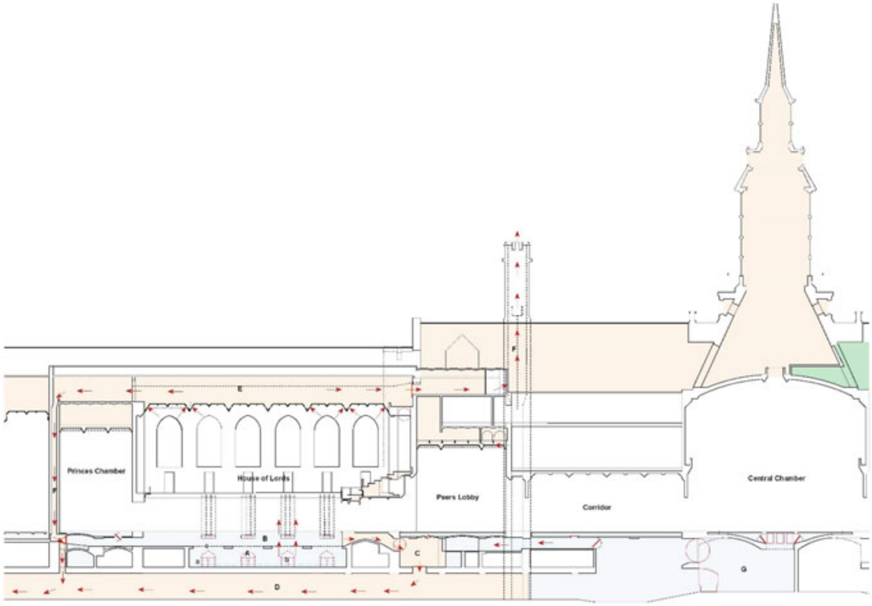

Fig. 13.8 Diagrammatic cross-section showing environmental strategy of House of Lords (Author's own drawing) Key: **A** Lower air chamber, **B** 'Equalising chamber,' **a** steam batteries (heating), **b** inlets facing Peers Court/State Officers Courts, **c** valves between lower air chamber and equalising chamber, **C** Downpull shaft 1: downward extract through floor at Bar end of House, **D** Vitiated air channel at basement level, which is linked to the Victoria Tower shafts, **E** Vitiated air chamber above ceiling, **F** Downpull shaft 2: conveys vitiated air from ceiling to basement passage, **F** Peers Shaft, **G** Central Air chamber

During sittings the Usher of the Black Rod, and the Lord High Chancellor, who was the presiding officer of the House of Lords, acted as liaisons between the Lords and the attendants. They held the responsible for managing the collection and review of feedback, and were also authorised to give instructions for changes [39]. Sir Augustus Clifford, who served as the Black Rod from 1832 till 1877, reported that his responsibility was to review the complaints made by individuals Lords, and if necessary, give instructions to a team of attendants for ad hoc adjustments to ventilation or climate [40] (Figs. 13.10 and 13.11).

13.3.1 Integrating Window-Induced Ventilative Cooling

Gurney also introduced openable windows inside the House of Lords, discarding the idea of permanently sealed debating chamber [41]. From 1847 up until 1854 the stained glass windows were fixed as Barry and Reid intended the space to be

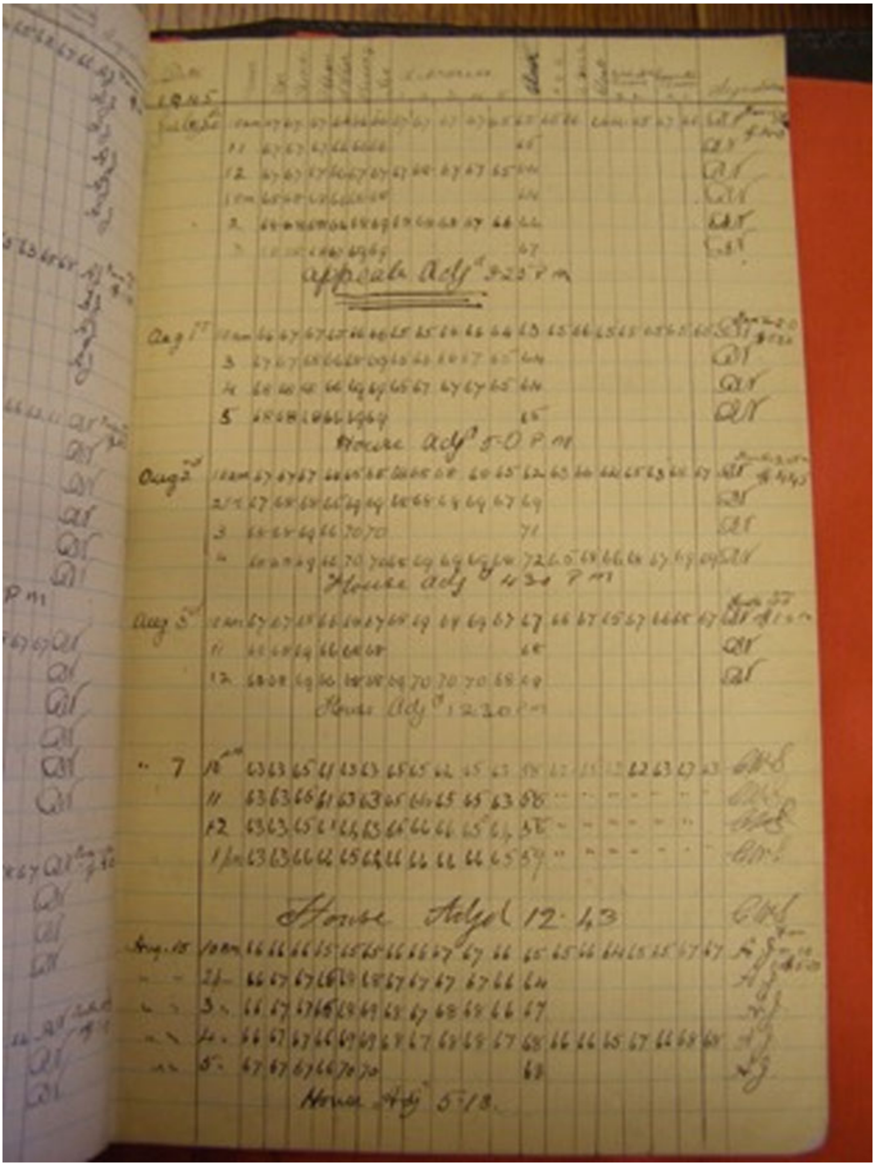

Fig. 13.9 Sample page from monitoring log-book, showing temperature readings taken during sittings between 30 July to 15 August 1945. ('Temperature book House of Lords, from 26 March 1943 to 1 July 1947, Parliamentary Archives, OOW 5 series, book 4)

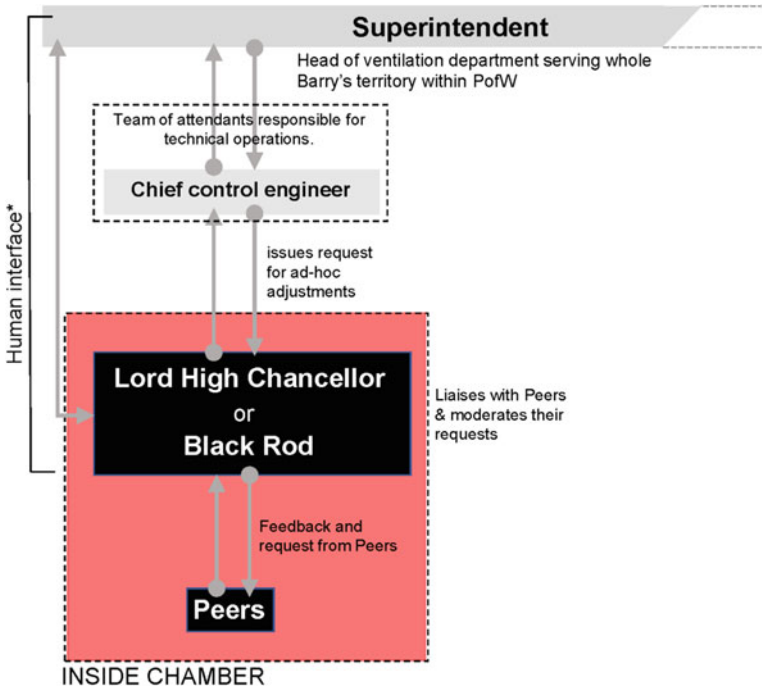

Fig. 13.10 Formal procedures regulating interaction between Peers and technical staff (Author's own drawing)

completely sealed from the external atmosphere, aiming to exclude external air pollution and to achieve a more tightly controlled indoor climate. Alfred Meeson, who acted as superintendent of the ventilation during the period, reported that the windows comprised two layers of fixed glazing, constituting an inner layer of stained glass and an external layer of clear 'plate glass.' He noted that its purpose was '*to preserve an equable temperature in the House in very cold weather, by providing space or stratum of air between the two glazings, which would prevent the cooling action of the external atmosphere upon that of the House*,' [42] but also reported that it would keep the interior cooler in summer. Following recommendations of the Select Committee of 1854, these windows were altered retrospectively to integrate operable sections for natural cross-ventilation. In the upper part of each of the 12 windows, two sections were made openable and were equipped with crank mechanism that enabled attendants to operate them remotely. Remains of the window opening mechanisms can still be found on the exterior of the House (Fig. 13.12). Roller blinds had been fixed externally on the west and east elevation to protect the Lords from the glare of the low angle sunlight in the afternoon or morning [43] (Fig. 13.11). During the winter months the windows were temporarily resealed by covering the operable sections with exterior glazing, providing thermal insulation and improve airtightness [44]. Despite these changes, Gurney did not proposed to abandon the original concept of a

Fig. 13.11 Historic photographs, 1868, showing the interior of House of Lords with open windows admitting sunlight (British Library)

climate controlled chamber. The use of cross-ventilation, facilitated through operable windows, was not intended to substitute or complement the stack ventilation during parliamentary sittings. In a letter, dated 17 June 1854, Gurney wrote it was introduced exclusively for '*freshening the House*' before and after the House was sittings [45], and in May 1854 noted that there use during sittings would only be advisable under certain weather conditions [46], It had to be kept closed during strong winds or when the outdoor temperature was too hot or cold [47]. Gurney, however, did not fundamentally oppose a more extensive use of windows. He noted that it would be at the discretion of the Lords themselves to determine when windows were to be opened. He also admitted that it could help improve comfort during warm weather through increased air movement.

13.4 A System in Use

1869–1938.

After Gurney's interventions in the mid-1850s the system remained largely unchanged for seventy years, but it underwent several post-occupancy studies and offered detailed into the performance of the historic cooling strategies. The number

Fig. 13.12 Exterior of window in House of Lords, showing closing mechanism (Author's own photograph, 2019)

and scale of technical inquiries into its performance was small compared to those undertaken inside House of Commons. This was largely due to the fact that the challenge of providing adequate ventilation or climate control inside debating chambers was not as severe inside the House of Lords as sittings were generally smaller and shorter. Two studies, published in the *Antiquaries Journal* (covering period from 1852 to 1854) and *Building Research & Information* (from 1854 to 1941), show that the House of Commons was subject of large numbers of parliamentary inquiries and scientific studies, and it also underwent several physical alterations. Over the same period studies in the House of Lords were confined to several smaller inquiries, conducted in 1869 and 1912, and one larger scientific study conducted between 1935 and 1938. One of the earliest inquiries were conducted in the summer of 1869, responding to complaints from Peers. A discontent with the climate inside the chamber was voiced by several Peers during a sitting on 16 July 1869. Their main concerns was the chill produced by the current entering through the floor, and the Lords also expressed their objecting to being placed inside a sealed room. The Earl of Carnarvon described Gurney's system as '*extremely complicated and highly scientific arrangement*' and reported that complaints had been made recently '*on all sides, sometimes of the frigid and some of the torrid zone*'. Earl Stanhope reported that the atmosphere at times felt hot, but at same time the Lords got chilly feet from the air introduced through the floor. He said that '*whilst hot air prevailed above, the feet of the noble Lord were exposed to currents of cold air, which came in from below*'. The Duke of Montrose reported that '*it seemed almost impossible to admit fresh air without causing strong draughts, and cold air all came underneath the benches*'. The Earl of Kimberley and Marquess of Salisbury had objections towards the idea of a sealed environment and advocated adopting a more natural solution, involving the use of windows. The Marquess describes the system as 'artificial' and felt that Peers insufficient personal control over their environment, and the Earl felt that they were at the mercy of the engineers, noting that '*horrors*' were '*endured in that House during the last few days from proceedings of the ventilation philosophers in whose power they were'*.

On 27 July, eleven days after the sitting, John Percy, who had succeeded Gurney as the superintendent of the ventilation, was summoned to give oral evidence to a Lords Select Committee on Office of the Clerk of Parliament, reviewing some of these issues Peers had raised. In his account he referred to the practical challenges of preventing overheating and draughts, which shows that the criticism was not unjustified. Percy reported, that there were no difficulties with controlling the climate during cold weather and under normal levels of occupancy, but the challenge was to maintain comfortable conditions during hot weather and under crowded conditions. The ability to counteract overheating by either injecting cooled air or boosting the ventilation rate was limited due to risk of cold draughts, which depended on the velocity and temperature of the supply air. It was constrained by physiological factors. As the fresh air was introduced through the floor, exposing Peers' legs directly to the current, it was not possible either to introduce cold air or significantly increase the speed without causing discomfort. Percy described his experience with this issue during an important debate held on 18 June 1869. In this day the Lords were debating the Irish Church Bill and the chamber was unusually crowded. In attempt to counteract overheating Percy's staff increased the ventilation rate and also lowered the supply air temperature to 59F, but he received a large number of complaints, and several '*Peers came down to me [Percy] in the air chamber under the House, and complained of cold draughts to their feet*' [48]. Percy thought that '*it is exceedingly objectionable to allow jets of air to impinge upon the legs*' and noted that the atmosphere was '*agreeable to the largest number of persons*' at a temperature of 62 °F (16.67 °C) to 64 °F (17.78 °C) if the velocity does not exceed 1 feet 6 inches per second (about 0.457 m/s), (which equates to 90 feet per minute—about

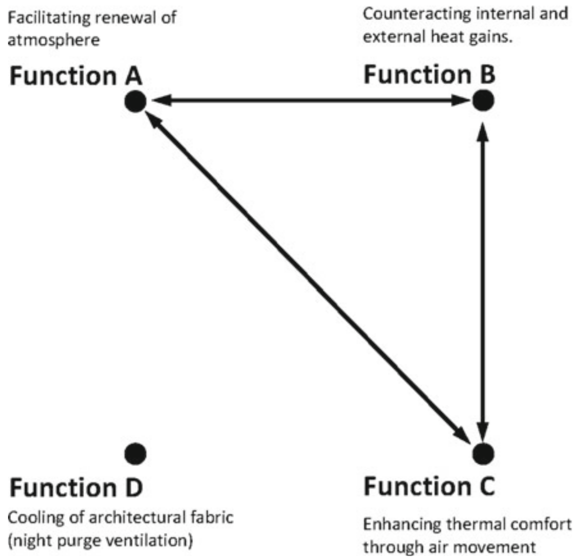

Fig. 13.13 Diagram showing 4 functions of ventilation, three of which are related to ventilative cooling. Functions A, B and C are closely intertwined and cannot be controlled separately (Author's own drawing)

27.43 m/min). This illustrates challenges with the use of ventilative cooling from an operational perspective. Attendants were faced with the challenge of reconciling the requirements of the different, yet closely intertwined environmental functions of ventilation (Fig. 13.13). In addition to renewing the atmosphere (A), ventilation was utilized as means to (B) reducing the indoor air temperature, (C) harnessing the cooling effect of air movement, (D) and also to cool the architectural fabric, following the principal of night-purge ventilation. Whilst the latter could be delivered at times when the chamber was unoccupied, the other three functions could not be addressed separately and had to be carefully balanced to avoid conflict. The ventilation rates required to reduce the internal air temperature or maintain a good air quality, for instance, could result in air movement that were below or above the levels considered desirable from a thermal comfort perspective.

Similar issues were raised again in the summer of 1878. It was brought up by Lord Granville during a sitting on 22 July 1878. He complained about the excessive heat in the chamber, highlighting that the indoor temperatures in July had got to 75 °F (23.89 °C), and also ask Lord Chancellor if the House of Lords, could be provided, similar to the House of Commons, with a cooling system involving the use of ice. In a written reply to Granville, dated 19 July 1878, John Percy claimed that the problem was caused by the opening of windows as it weakened the current of fresh air introduced through the floor, resulting in the temperature in the lower part of the chamber to rise. Percy, referring to his experience with operating the system during the 1860s and 1870s, claimed that the stack system could achieve larger ventilation rates and could maintain a lower air temperature if the chamber was sealed and supplied with cooled air through the floor [49]. During the sitting on 18 July 1878, for instance, Percy's team had closely monitored how the windows affected the internal temperature. From noon till 5 pm, when the House was sealed, the temperature was 71 °F (21.67 °C), it rose to 73 °F (22.78 °C) after five of the operable window units had been opened, and at 6.30, when this number was increased to eleven, it had reached 75 °F (23.89 °C).

It has to be noted that windows were opened frequently during sittings than Gurney had intended. Individual Lords frequently requested windows to be opened [50], claiming that it made the interior feel more comfortable. By the 1870s natural ventilation was deployed routinely during sittings in summer and a formal control regime, regulating the opening and closing of windows, was introduced. The aim of this regime was to limit the admission of direct sunlight, which caused issues with glare and heat gains [51]. The Lord Chancellor, who was responsible for supervising the operation of the windows during sittings, reported that he ordered them to be opened at five every evening, and at times also gave instructions for the ad hoc adjustments. He reported that solar gains were a significant issue during sunny weather and that external blinds were drawn across the windows to reduce them. During the daytime permission was only granted for '*windows to be opened on the shady side of the House*,' whilst external blinds were drawn across the other side to protect the interior from the sunlight [52]. A sophisticated operational regime regulating the opening and closing of windows was also adopted in the House of Commons, which has been discussed in detail in the author's article in *Building Research and Information* [53]. These changes were significant as they illuminated the limitation of that Gurney's system. His original idea of creating a sealed and climate controlled space was temporarily abandoned during hot weather. A new operational regime, integrating direct natural ventilation, was introduced retrospectively to overcome these limitations. Despite his concerns about increased air temperatures, Percy also recognise that the windows were enhancing comfort by introducing air movement. He noted that '*if air moves at a high velocity, you can cool yourself even with warm air, upon the principle of fanning*'. In retrospect it could be argued that the two different modes of ventilative cooling had emerged. The first was **mechanically-induced ventilative cooling**, utilised when the chamber was operated in a sealed mode and air was introduced inclusively through the floor. The second type was **window-induced ventilative cooling**, which was deployed when the chamber was operated in a natural mode, which mostly in summer, and it focused on improving comfort through increasing air movement.

The complaints give the impression that the system was incapable of preventing discomfort during warm weather. Historic measurements of internal temperatures, however, suggest that overheating issues occurred for brief periods during the summer. But what temperatures were encountered inside the chamber?

Monitoring data collected by attendants in the summer of 1869 show that the temperature ranged from 63 °F (17.22 °C) to 75 °F (23.89 °C) in July. The recordings in a log book covering the period from 1943 to 1947 suggest that overheating issue could be serious but were limited to brief periods, lasting only few days each year. In the summer of 1943 the highest daily peak temperatures, recorded between 27 July 5 August, were between 71 °F (21.67 °C) to 73 °F (23.78 °C), but for the rest of the summer, they stayed within 64 °F (17.78 °C) to 69 °F (20.56 °C). In 1944, when readings were only recorded in June, the temperature was between 61 °F (16.11 °C) and 66 °F (18.89 °C), and from June to August 1945 the peak indoor temperatures ranging from 64 °F (17.78 °C) to 70 °F (21.11 °C), only reaching 71 °F (21.67 °C) on only a single day. In June and July 1946 the temperatures recorded from 60 °F (15.56 °C) to 75 °F (23.89 °C), and two periods with higher temperatures encountered. During the first period, which occurred between 2 July to 12 July, the temperature was constantly between 70 °F (21.11 °C) and 74 °F (23.33 °C). In the second period, which was between 23 to 26 July, it ranged from 69 °F (20.56 °C) to 75 °F (23.89 °C). The highest temperatures occurred in the summer of 1947, beginning in early June 1947 (2–4 June) with temperatures constantly between 74 °F (23.33 °C) and 81 °F (27.22 °C). Another period of overheating occurred between 24 June and 1 July, when the peak indoor temperatures reached 71 °F (21.67 °C) to 75 °F (23.89 °C).

Although the data is suggesting that overheating issue were confined to relatively brief periods, individual Lords repeatedly voiced their discontent publicly within the chamber, and pressure to improve comfort became the driving force behind further investigations in the twentieth century. These began with an inquiry into the feasibility of remodeling the existing system between 1911 and 1912, and was followed by study inside the House of Commons (1913–1923), during which the impact of the historic use of ventilative cooling was re-examined from a physiological perspective, drawing on new scientific research and utilizing modern methods of air flow simulations.

13.5 The Re-appraisal of an Old System

Studies of ventilative cooling, 1911–1937

In July 1911 the Secretary of the Commissioner of Works received a note reporting that the '*ventilation is not nearly sufficient in hot weather and the atmosphere is at times very oppressive,*' and requesting that a larger number of windows are made to open [54]. Overheating issues had occurred during several sittings in July and August 1911, and had led to an increase in the number of complaints from Peers. The engineers at the Office of Works subsequently reviewed the issue. The chief engineer believed [55] that the existing system was not capable of providing the higher ventilation rates required to prevent overheating in the summer, and highlighted that this issue was further accentuated by the fact that debates had become longer and better attended than in the past. On 27 October 1911 he wrote to the Lord Chamberlain that '*a great deal of complaint—quite justifiable I thought- of the heat during the debates last August*' and that something needs to be done to prevent it from re-occurring in future summers. He subsequently requested the resident engineer of the Houses of Parliament, Arthur Patey, to develop proposals for improving the existing system. Patey argued that the problem could not be resolved by simply opening the windows, but required more substantial and expensive interventions [44]. Similar to Percy in 1860s he claimed that the opening of windows would aggravate, not reduce, overheating problems. In April 1912 Patey presented two schemes for replacing Gurney's system with modern mechanical ventilation driven by electric fans. In one of his schemes he proposed to reverse the direction of the ventilation by moving the main air supply to the ceiling of the chamber. This have involved introducing two large channels, linking the existing ceiling to new air intakes at roof level. In his final report Percy wrote that a supply from the ceiling would eliminate the existing problems with currents entering near the body, stressing that the '*feet are very sensitive to ascending air currents.*'

13.5.1 Problems Revisited in the House of Commons

Due to the high cost of Patey's proposition the inquiry inside the House of Lords was postponed, but further investigations into the cooling effect of internal currents were undertaken inside the House of Commons. This study was significant as it was the first time that the physiological impact of air movement inside the chambers was examined using scientific methods, and it also informed the direction of later studies inside the House of Lords. This was informed by new research into the physiological effects of climates undertaken by Dr Leonard Hill, a physiologist from the Medical Research Council's (MRC) Department of Applied Physiology—these studies are examined in more detail by Schoenefeldt [37]. His research strong influenced the development of thermal comfort standards for air conditioned environments in the US during the 1920s [56, 57] The first part of the investigation was led by a Select Committee, appointed in 1913, and was continued between 1920 and 1923 by the Office of Works in collaboration with the National Physical Laboratory (NPL). The Committee was appointed in response to a growing discontent that MPs had voiced in several sittings between 1912 and 1913. They criticized the atmosphere for being too warm and uniform and complained about draughts around the legs [58–60]. The latter was been longstanding issue, but had become more severe following the installation of electric fans and reduction in the size of floor inlets in 1904.

The Committee engaged Hill, who between January and March 1914 examined the existing conditions and proposed a scheme remodelling the ventilation based on physiological criteria [61]. In his first report he identified the physiological effect of currents entering through the floor as the main problem. He wrote that the air '*caused a draught which had a cooling effect on the feet and legs of the members whereas there was not sufficient movement of air round their heads and shoulders*' [62]. Hill undertook further measurements of thermal conditions during sittings, using caleometers and kata thermometers, which were scientific instruments used to quantify the cooling effect of currents. Measurements taken under crowded conditions in March 1914 revealed that the cooling rate at the feet was twice as high as around the head. Hill also argued that the currents, aside from producing cold feet, were also responsible for the 'feeling of heaviness, colds and headaches', which had previously been associated with poor air quality [63].

To overcome this problem he recommended replacing the use of floor inlets and with new apertures set at a higher level [64]. These apertures were to be introduced in the face of the galleries, which, located above MPs' heads, allowed to inject fresh air horizontally into the chamber without exposing them to direct currents. He also recommended maintaining a different type of indoor climate. Arguing that the sense of drowsiness reported by MPs was caused by the breathing of warmed air, he advised a reduction in the atmospheric temperature and the provision of warmth through radiant heaters between the benches. He also considered the conditions as too uniform and recommended introducing a more physiologically stimulating climate with gentle variations in temperature and air movement. The latter was to be achieved by alternating the direction of the currents.

In February 1914 The Committee endorsed the scheme, and after the First World War the feasibility of Hill's proposal was evaluated through experiments. To test the impact of the proposed changes the NPL conducted air flow simulations inside scale models, which were followed by test with a life size mock-up inside the debating chamber—these studies have been examined in detail in Ref. [65].

13.5.2 Return to the House of Lords, 1935–37

In the mid-1920 a few changes were made to the House of Lords, but these did not go beyond the installation of a simple mechanical air extract to boost the ventilation capability. This replaced the original coke fires. Inquiries into further and more substantial alterations, however, were conducted in the 1930s. This was initiated by a motion that the Marquess of Linlithgow had presented to the House on 24 July 1935. He demanded the appointment of a Select Committee charged with leading an inquiry into the feasibility of introducing 'an up-date air-conditioning' system, arguing that this new technology would great control over the climates'. The motion was withdrawn after agreeing that engineers at the Office of Work would lead the inquiry on behalf of the Lords. A large study, focusing on the climate conditions inside the chamber were conducted between 1935 and 1936, which involved a collaboration between J.A. Macintyre, chief engineer at the Office of Works, and the physiologist Dr Thomas Bedford from the MRC, who, similar to Hill, was leading researcher into thermal comfort [66].

The aim of the study was to examine the causes of discomfort, taking into account the effect of temperature, humidity and air movement, and determine if air conditioning would be required to overcome them [67, 68]. From October 1935 to September 1936 the temperature and relative humidity of the atmosphere inside the chamber was systematically monitored using self-recording thermometers and hygrometers, yielding data for a whole year [69, 70]. In addition Bedford undertook two in-depth studies examining the velocities of the internal currents, one focusing on the winter [71], the other on the summer conditions. The chief engineer also produced two reports, summarising and discussing the findings of the monitoring and Bedford's studies. The monitoring was originally intended to be complemented by user studies, looking at the Peers' experience of the climate conditions. For this purpose Bedford proposed to undertake (1) user surveys, involving the use of paper questionnaires,

(2) face-to-face interviews and (3) also to ask a few Peers to keep a personal log on their experience [72]. This part of the study was developed and discussed between December 1935 and February 1936, but was abandoned due reluctance amongst the Lords to participate [73–75].

The studies focusing on the summer conditions was undertaken between June and October 1936 [76]. Measurements were taken in nine locations at head height and floor level. In addition temperature, measurements were taken of the velocity, variability and the cooling rate of air movement, using hot-wire anemometers and kata-thermometers. In his final report to the Office of Works, dated 18 November 1936, Bedford concluded that the high indoor temperatures, combined with insufficient air movement, were the main cause of discomfort. The original data shows that high indoor temperature were common during the summer (Fig. 13.14). Between November and March the indoor temperature ranged from 56 °F (13.3 °C) to 70 °F (21.1 °C) and on most days stayed within 62 °F (16.67 °C) to 65 °F (18.3 °C). During the warmer weather between May and August, however, it had reached 70 °F (21.1 °C) or above on 33 days. The highest temperatures were recorded in June. In this month it range from 64 °F (17.78 °C) to 77 °F (25 °C), reaching 70 °F (21.1 °C) or above on 14 days. Referencing thermal comfort standards for factory workers, Bedford argued that it exceeded air temperature of 64 °F (17.78 °C) to 68 °F (20 °C) should be perceived as '*comfortable by the majority of persons when sitting still*.' Bedford's report did not include data on occupancy or outdoor temperature, an analysis, undertaken by the author using historic weather data from the Kew Observatory, suggest that when the indoor temperatures reached 70 °F (21.1 °C) or higher, the interior was always marginally cooler than outdoors. The different varied from 1 °F to 7 °F (0.56 °C to 3.89 °C). This, however, was rarely sufficient to mitigate overheating.

The study also found that the velocities of air entering through the floor was much lower during summer month than during the heating season, further aggravating the sensation of warmth. Due to the natural convection produced by the heated air, the velocities were three times as high, typically around 40 feet per minute, but at times reached up to 80 feet per minute. Bedford concluded that the atmosphere generally did not have enough air movement. None of the velocities recorded by Bedford reached 100 feet per minute, which today is considered the threshold at which currents become noticeable. He argued that the use of a large perforated floor had indeed succeeded in meeting Gurney's objective of keeping velocities very low, even when the ventilation was operating at the maximum rate of 8 air changes per hour. According to readings taken between June and October 1936 the average air velocity was 8 to 14 feet per minute. This led Bedford to conclude that the chill around the feet was likely to have been caused by the low temperature rather than the velocity of the incoming air. The currents entering through the floor never reached velocities high enough to cause discomfort around the feet. He wrote that '*impression of draughts near bar may be due to the lower temperature and greater variability of the air currents*' [76].

Another set of measurements was taken between on 24 June and 17 August 1936 to determine the relative effect of the fan, windows and heating system on the strength

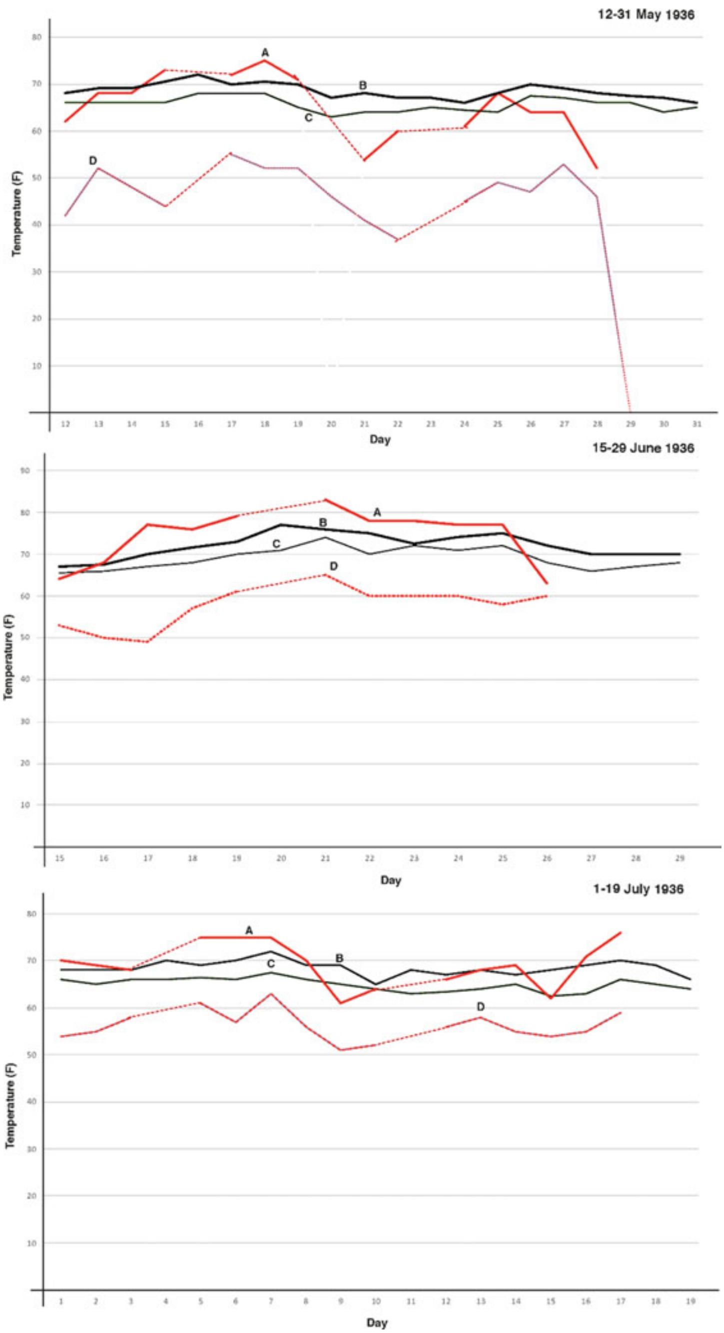

Fig. 13.14 Graph: Temperatures recorded inside Lords chamber, overheating periods between May and July 1936 (Author's own graph)—Key: **A** Maximum outdoor temperature (daytime), **B** Maximum indoor temperature, **C** Minimum indoor temperature, **D** Minimum outdoor temperature

of the internal air currents. Bedford undertook separate observations of the conditions when the chamber was operated in a sealed mode or with the windows open. These showed that the opening of windows only led to a marginal elevation in the indoor temperatures, yet noticeably improved thermal comfort by providing more air movement inside the chamber. These not only caused a significant increase in air movement but also resulted in greater variation of speed [77, 78], both of which, he argued, were important for comfort. He wrote that the '*rather greater velocities which prevailed when the windows were open had a noticeable influence on our comfort*,' and the air also felt fresher, but when closed '*there was a regular feeling of deadness*.' This was significant as it provided, for the first time, scientific evidence that open windows were improving thermal comfort, which hitherto had only been an assumption based on personal experience.

The issue with the use of natural ventilation, however, was that it was not reliable, as it was dependent on the external wind conditions. On 10 July 1936, when there was 'slight breeze outside' the windows were found to significantly increase the air movement. During the time the chamber was sealed the velocity was observed to range from 5 to 20 feet per minute, but this increased to a range of 10 to 65 feet per minute after the windows had been opened [78] (Fig. 13.15). On 17 August 1936, when the weather was 'calm', the velocity was no higher than 35 feet per minute

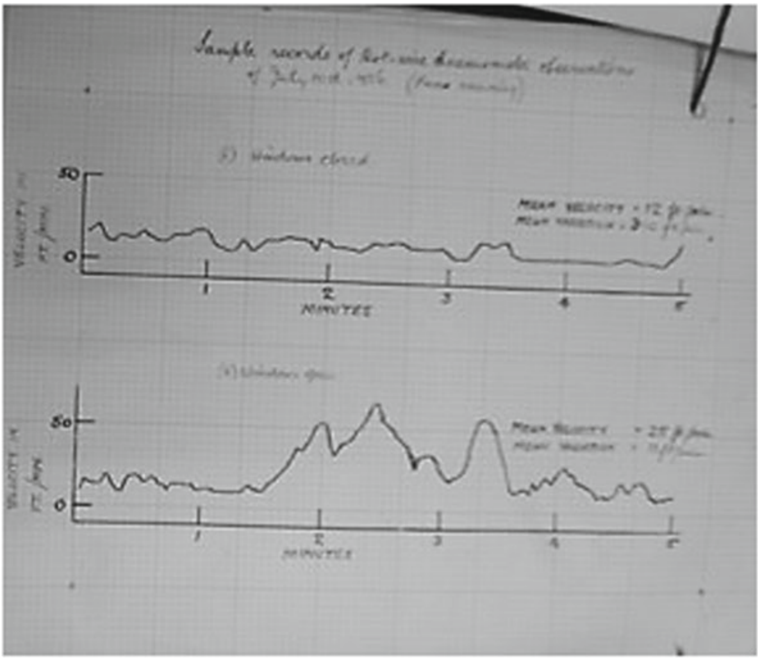

Fig. 13.15 Recordings of velocities, 10 July 1936, showing effect of windows (Report from Thomas Bedford to Chief Engineer of Office of Works, 18 November 1936. (NA: Work 11/358)

(about 10.67 m/min) [79].[2] To improve thermal comfort Bedford proposed replacing the evaporate cooling system with mechanical refrigeration and but to increase the air movement with the aid of mechanical ventilation. Arguing that '*increased turbulence*' is needed to make the air more 'refreshing' during hot weather he proposed, similar to Hill's scheme for the House of Commons, to move the outlets from the floor to the gallery level and inject air horizontally above the heads. Air was to be introduced at high velocities from both sides simultaneously, producing eddies in the centre, which, Bedford claimed, would '*prevent stagnation at the level of the benches*'

In two reports, dated 7 and 17 December 1936, the chief engineer reviewed the findings of Bedford's studies and also made a series of recommendations. He concluded that the main issue was summer cooling, and dismissing the historic water sprays as ineffective, he recommended introducing mechanical refrigeration [80], but as an initial step he proposed a simple intervention: agitating the atmosphere with the aid of open ceiling fans. On 16 February 1937 a Joint Committee, composed of scientists from the MRC and DSRI, reviewed Bedford and engineers reports. Its advice was to provide night-time ventilation to cool down the fabric, minimise the admission of outside air during daytime, which involved keeping the building sealed, and to increase in air movement mechanically, using ceiling fans that could be operated at varying speeds, ranging from 40 to 60 feet per minute [81]. None of these recommendations, however were ever realized, and the idea of enhancing comfort through a new approach to ventilative cooling was also discarded after the Second World War. Several investigations, undertaken in 1950 and 1963, were limited to feasibility studies looking at the installation of air conditioning [82–84]. Responding to increasing pressure from the Lords it was first piloted 1965 and fully implemented between 1966 and 1966 [85].

13.6 Conclusion: Evolving Practice

Taking a historical perspective this chapter has investigated the practical application of ventilative cooling practices in the House of Lords. These practices, observed over a period of 100 years, were characterised by a focus on the environmental and physiological rather than technological dimension of climate control.

The environment was controlled manually, and it involved extensive interactions between attendants, users and the technology. The ability to effectively manage the internal conditions was highly dependent on the continual gathering of data about its performance in use, including measured data on the physical conditions as well as qualitative data on users experience.

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[2]Note: It is to be noted, however, that these were still very low rates from a physiological perspective. According to modern standards velocities of 50 feet per minute (15 m) or less are unnoticeable, only when above 50 and up to 100 feet per minute (30 m) produce noticeable yet pleasant currents. Above they 100 become constantly noticeable, but only above 200 feet (60 m) become a nuisance.

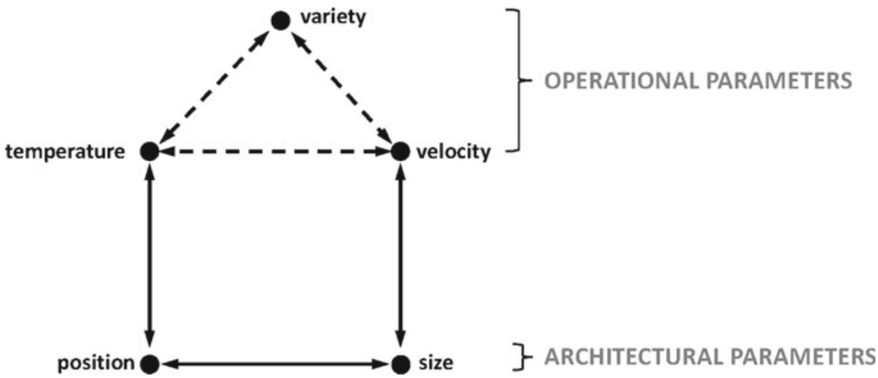

Fig. 13.16 Diagram showing relationship between architectural and operational parameters addressed by inquiries into historic ventilative cooling strategies (Schoenefeldt)

In the context of the day-to-day operations attendants acquired such knowledge through environmental monitoring, direct observations and also by reviewing reports from users. It was complemented by more in-depth inquiries, which were led by scientists and engineers. These inquiries engaged with the operational and physical design parameters of ventilative cooling (Fig. 13.16). Operational regimes were adjusted, existing arrangements remodelled, and several design studies, anticipating more intrusive physical alterations, were also conducted in the 20th century. The understanding of ventilative cooling in practice was not static but evolving.

In these studies much focus was on the cooling sensation caused by air movement, recognising its risk to cause discomfort but also its potential to enhance thermal comfort during warm weather. It was an important physical factor alongside temperature and humidity, but at the core of these inquiries, was an engagement with the subjective nature of thermal comfort. This resulted in the need for collaboration with physiologists, who provided the specialist knowledge and skills required to evaluate and improve the thermal environment. The day-to-day implementation of ventilative cooling principles was also highly dependent on user participation. Users could not be treated as passive observers, but as active participants in an ongoing process of evaluating and adapting the thermal environment. As such, it could be argued, that ventilative cooling was an inherently socio-technical practice.

Today the physical features, let alone the more intangible cultural practices associated with its day-to-day operation, have become redundant. This was the direct result of the introduction of modern mechanical services in the mid-20th century. Significant architectural features, such as the perforated floors, are currently hidden underneath a new floor, equipped with an array of modern inlets grills. These and earlier changes in the 19th century have illuminated the extent to which historic practices of environmental control had affected the House of Lords architecturally, and as such also their significance to building conservation. The redundant features are physical evidence of historic approaches to ventilative cooling, and archival research, has helped to reconstruct their design, operation and performance. This raises the question if a deeper understanding of past environmental practices that engages critically with their potentials and limitations, could inform contemporary conservation practice. In buildings of high historic significance, where the scope for physical interventions is limited, a critical reconstruction of historic practices could potentially provide a new approach to balancing the requirements of heritage and sustainability [86–88].

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